CAPACITORS

Their Use in Electronic Circuits

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CAPACITORS

Their Use in Electronic Circuits

By

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FOREWORD

This book is not a treatise on capacitors * and neither depth nor originality is claimed for the material. It is in the nature of an answer to a question—to certain typical questions that came up with impressive regularity in the experience of the writer during 17 years of development work on wave filters and capacitors at the Bell Telephone Laboratories.

These particular questions did not concern the multitude of details which come up as a matter of routine in the process of development engineering. They were related to the basic factors which control the characteristics of capacitors and to the considerations upon which hinges success or failure in electronic circuits. There was a time when capacitor types were so few and circuit requirements so lenient that a knowledge of these controlling factors could, perhaps, be left safely in the hands of capacitor specialists. Nowadays, as experience has amply demonstrated, the circuit designer cannot dispense safely with the protection afforded by a broad understanding of the capacitor problem if he is to avoid the pitfalls incident to the growing severity of operating requirements in electronic circuits and to navigate intelligently through the multiplicity of capacitor styles on the market.

For this purpose, the average circuit designer does not require an elaborate textbook or a list of capacitor types, dimensions and characteristics which merely prove bewildering to the unpracticed eye. What he needs are perspective and judgment—a basic working picture, which will enable him to evaluate circuit requirements in terms of capacitors, weigh the information in commercial catalogs and, in general, illuminate his dealings with capacitor experts. Although not in itself dif-

* The term "capacitor" is used instead of the older word "condenser" in conformity with "American Standard Definitions of Electrical Terms" sponsored by American Institute of Electrical Engineers.

ficult to grasp, this essential knowledge is somewhat inaccessibly stored away in the minds of capacitor specialists or scattered variously over books, technical publications and information published by capacitor manufacturers. This book is an attempt to bring the material together in form suitable for quick reading—for example, on railroad trains, where, under wartime pressure, it was largely devised and written. The author gratefully acknowledges both help and comments from many friends at the Laboratories engaged in the study and development of capacitors and dielectrics.

M. B.

Bell Telephone Laboratories, Inc.
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INTRODUCTION

That spark which leaps from our fingertips to the wall switch on a dry day is a sharp reminder that we have electrical capacitance, the property of storing electric charge or energy. It is a property exhibited by any two electrical conductors separated by an insulator. In this instance, the body, as one conductor, stores charge with respect to the earth as the other conductor, the charge being developed through friction between shoes and carpet. There is capacitance between us and the cat when we stroke its fur and draw sparks, between a charged thundercloud and the earth, between the road and our automobile which may, incidentally, acquire through accumulation of static charge on above-ground potential of 10,000 volts under favorable conditions. Capacitance is part and parcel of our environment.

Those of us who build electronic circuits know the plague of unwanted capacitance in creating parasitic linkages among different parts of a circuit. In inductance coils and transformers, the "distributed" capacitance between the wire turns tends to degrade performance by causing the effective inductance to deviate from the ideal or geometric inductance. In open-wire telephone lines and in cables, distributed capacitance has the undesirable effect of by-passing the higher frequencies upon which the intelligibility of transmitted speech largely depends. It was indeed the need to compensate for this unwanted capacitance that stimulated the development of the loading coil. In all these instances, the problem is one of reducing or neutralizing the effect of unwanted capacitance. Diametrically opposite is the function of a capacitor, which is to provide wanted capacitance, in concentrated or "lumped" form, in controlled amount and conveniently packaged. To furnish this is the task of capacitor engineering.

The specific idea of a "condenser" dates back to the invention of the electro-phorous and shortly thereafter of the Leyden jar in 1745. For a great many years, students of electricity had been producing electric charge, but the amounts were usually small and evanescent. Up until this time they had not thought specifically in terms of the idea of capacitance. Here at last was a device capable of storing a large electric charge in a small space. For this reason, Volta in 1782 aptly named such devices "condensers." The invention of the Leyden jar focused attention on the idea and on the possibility of storing electric charge.

Invented in Holland and named after the town of its origin, the original Leyden jar consisted of a glass vial containing water and plugged with a cork through which a nail passed to touch the water. The water constituted one electrode, the other being provided by the hand which held the vial. This device immediately excited widespread interest among the natural philosophers of those days because of the impressive electrostatic charge that could be stored in it as compared with earlier devices. Further study by Mr. J. H. Winckler of Leipzig soon disclosed that a chain could be substituted for the hand as an electrode. Shortly thereafter, in 1746, Dr. John Bevis of London lined the inside and the outside of the glass vessel with lead sheet and thereby developed the prototype of modern capacitors, namely, two metal electrodes of relatively large area separated by a dielectric of uniform thickness. Most modern capacitors are variations of this fundamental form differing only in materials and dimensions.

How successful were those intrepid, early investigators in trapping "electrical fluid" with this new device is vividly portrayed in an experiment carried out by the enterprising Mr. Winckler some two hundred years ago:

". . . the first time he tried the Leyden experiment, he found great convulsions by it in his body; and that it put his blood into great agitation; so, that he was afraid of an ardent fever, and was obliged to use refrigerating medicines. He

also felt a heaviness in his head, as if a stone lay upon it. Twice, he says it gave him a bleeding at his nose to which he was not inclined. His wife (whose curiosity, it seems, was stronger than her fears) received the shock twice, and found herself so weak, that she could hardly walk; and a week after, upon recovering courage to receive another shock, she bled at the nose after taking it only once." *

Those of us who have casually touched a charged high-voltage capacitor will readily sympathize with Mr. Winckler as he reached for the refrigerating medicine.

Other investigators found that they could kill small birds with the discharge from a Leyden jar, and used the discovery to entertain the ladies of the French court. Later, Benjamin Franklin found he could kill a chicken by connecting Leyden jars in "cascade." He also tried to kill a turkey, but the native bird proved too tough. Then there was the famous experiment in which he hung a kite string on a Leyden jar to pull lightning out of the clouds and lived to announce the discovery that lightning is caused by electricity.

We may note in passing that, potent as these Leyden Jars appeared, their capacitance was only a small fraction of the amount frequently required in present-day electronic circuits. In those days, any device capable of storing a substantial electric charge for several minutes was apparently satisfactory. A Leyden jar of only one microfarad would be as spacious as an office elevator whereas, today, a capacitor of many microfarads may have to form only one part of an apparatus no larger than a lady's handbag of reasonable size.

Up until the advent of the alternating current circuit, the capacitor was to remain chiefly a laboratory device, familiar to students as a device for storing electric charge and investigating its properties. † It was not until the 1880's that ca-

* *The History and Present State of Electricity*, by Joseph Priestley, Vol. 1, page 107, 3rd ed., London, 1775.

† An interesting and detailed account of the history of capacitors is contained in a book entitled *Electrical Condensers*, by Philip R. Coursey, London, Pitman, 1927.

pacitors were first used on a commercial scale, and then it was in connection with the electric telegraph. Somewhat later came their use in the telephone. During the intervening 140 years, research, spurred by the invention of the Leyden Jar, continued to reveal the properties and behavior of capacitors and dielectrics. Notable was the work of Michael Faraday, in honor of whom is named the "farad," the practical unit of capacitance. Various investigators had observed that the ability of a capacitor to store charge depended on some specific property of the dielectric. It was Faraday who made a systematic study of this property and named it "Specific Inductive Capacity" or "Dielectric Constant." More than any other factor, the nature and condition of the dielectric determine the character of a capacitor.

Dielectric materials as diversified as paraffin wax and Gold Beaters Skin were the subject of experimentation. The year 1845 brought a capacitor made by piling alternate layers of mica and tin to provide the prototype of the modern mica capacitor. In 1876 came a capacitor consisting of interleaved layers of conductor and paper, wound to form a cylinder and subsequently impregnated with paraffin. Present-day paper capacitors are still made in this form. We read that, in 1893, paraffin-paper capacitors were used in commercial power circuits, but became so hot they had to be taken out, an incident foreshadowing the considerable study which would be required to adapt the paper capacitor to low-frequency power uses. By the end of the last century, capacitors were finding increasing use in industry.

Lord Kelvin and others had shown how the discharge of a capacitor might become oscillatory in character, a property which makes possible the oscillating circuit and the generation of electric waves. At the turn of the century we find Marconi using Leyden jars of elementary form to help generate electric waves in the first successful wireless transmission experiments. Later came the electron tube; it is through the electron tube circuit and its auxiliaries that the capacitor has seen its greatest expansion. The swift succession of developments

in telephone, radio and elsewhere which the electron tube made possible created an urgent demand for better, smaller and cheaper capacitors.

As a result, during the past quarter century, the making of capacitors has grown to be a major as well as a highly specialized branch of the electrical art. Rare is the electric circuit which does not employ at least one capacitor. The Bell System alone uses over 100,000,000 of them. From almost every angle, the circuit designer or builder of electronic circuits is confronted by the need to use a capacitor in one form or another.

To him it is likely to appear as that unavoidable package of microfarads to which space is reluctantly allotted, or the thing which must be added to a circuit after it has been fully designed and which could not be squeezed into the already overcrowded chassis even under hydraulic pressure. To the harassed capacitor specialist, it seems to be damned by all, intelligently used by few and adequately understood by none. All of this reflects both the inevitability of capacitors and the growing complexity of the art.

Too few of us realize that the provision of capacitors capable of meeting today's requirements of high-grade electronic circuits demands systematic engineering effort, aided by chemical and physical research and supported by rigid standards of manufacture. Naturally, this rapid growth has entailed marked growing pains and the problems have multiplied in step with the relentless pressure on apparatus designers to accommodate more apparatus and more power in less space. In 1943 the urgent need for high capacitor quality and for the standardization of types culminated in an extensive study by the American Standards Association and the War Production Board to establish national standards for the control of capacitors for military uses. Later the Army-Navy Electronics Standards Agency extended these efforts and issued improved standards for joint Army and Navy use.

To some, there may be a sour note in the radio repair handbook's advice to "check the capacitors" as a first step to

take when a set goes wrong; it is always a curt reminder that broken-down capacitors are a common cause of dead circuits. However, to correct any false impression which this undoubtedly sound advice may leave, we hasten to inject another idea, also amply supported by experience—that capacitors rarely fail when the operating conditions have been intelligently analyzed and specified and the capacitors themselves adequately designed and manufactured to meet them.

Rarely are defective capacitors traceable to the limitations of the capacitor art per se. The responsibility usually lies with ignorance, carelessness or an uneducated sense of economy.

It is, of course, the ultimate responsibility of the capacitor specialist to provide satisfactory capacitors. However, he is not always readily available to give advice. Between him and the customer lies the manufacturer's catalog presenting a multiplicity of capacitor styles and a maze of data and the salesman who, however cooperative, may not be sufficiently familiar with the engineering viewpoint. For this reason, it is a matter of enlightened self-interest for the designer of electronic equipment to have at least an elementary understanding of the problems faced by the capacitor designer and manufacturer, of the limitations imposed by materials and of the factors which spell the difference between a satisfactory capacitor and an unsatisfactory one in a specific circuit. Not least he should know how to temper the generous optimism which sometimes crops up in trade catalogs. Fortunately, this elementary knowledge need not be hard to acquire.

How much does he need to know? Perhaps this may be compared to inquiring as to what extent an automobile driver needs to be acquainted with the roads he travels. Obviously it is by no means essential for him to have a detailed knowledge of the roads, but he must know how to read road signs, distinguish byways from highways and above all to recognize clearly when he is headed downhill for a red light. Analogously the capacitor user need not burden his mind with details which properly belong in manufacturers' catalogs but he

must surely know the right questions to ask—key questions which are capable of revealing the good and bad points of the specific capacitor type he is selecting to use. These probing questions remain the same no matter what changes overtake the products of the capacitor art.

New operating requirements, new apparatus designs, new types of service—all may entail new danger signals. In the headlong development of electronic circuits during the past 25 years many a red light was passed heedlessly by. In case this judgment seems unfair to capacitor users we hasten to add (in a whisper) that even capacitor specialists failed to spot all the hazards. Notable danger points became evident only after numerous, apparently well-designed capacitors had collided fatally with the severe requirements created by the operating conditions in new designs of electronic equipment. In capacitor design as in capacitor selection the primary safeguard lies in asking the same right questions with a monotonous insistence every time a new capacitor or a new operating condition is involved. They illuminate dark corners for all of us to see.

How important it is to ask the right questions is illustrated by the following account of the adventures and vicissitudes of a certain piece of electronic equipment which we shall name "The Set That Jack Built." The story is purely fictitious and any resemblance to persons living or dead is, of course, purely coincidental. However, those who have had the challenging experience of developing high-grade electronic equipment to operate under severe conditions may be reminded.

It seems that Jack had the task of engineering a piece of electronic equipment. Since he was well versed in the theory of electronic circuits, the design he developed was in all respects meritorious and because he was also adept at mechanical design the set took shape as a masterpiece of compactness, lightness, and mechanical efficiency. So when the completed equipment finally appeared upon the laboratory bench for all eyes to see, his heart was glad. It was exactly what the doctor

had ordered. Even the vice-president of the company heard about it and came down to see it.

It had been a simple matter to select the various capacitors from commercial catalogs, using his carefully computed values for capacitance and operating voltage. These values were unmistakably marked on the capacitors for all to see. However, by way of double insurance, he personally tested each capacitor for capacitance and breakdown voltage. With a shrewd eye to economy of space and cost, he had selected the various items so that they would fit snugly in the nooks and crannies of the apparatus assembly.

None was surprised when the set fulfilled its theoretical promise as to performance—almost. There were a few sour notes. And after much patient testing, analysis and computation Jack found that the effective resistance of the low-capacitance paper capacitors he had chosen was so high that the transmission quality was objectionably impaired. It is indeed a moot point whether designers of electronic equipment who are accustomed to deal with really weighty matters should be expected to know that paper capacitors may exhibit large values of effective resistance, especially at the higher frequencies. However, the fact remains that, had he known this in the first place, he would have chosen the cheap and equally available low-loss mica capacitors, which he was now compelled to substitute for the paper capacitors in this part of the circuit.

After the set had been used for several days it is recorded that a single capacitor failed, but the incident aroused no special comment, and the defective part was replaced. When a few days later, the new capacitor also mysteriously failed, suspicion was aroused as to the suitability of the type and its voltage rating. This mystery further deepened when tests showed the steady voltage across this capacitor to be sufficiently under the working voltage marked on the capacitor to satisfy even the most conservatively minded. Eventually, by analyzing the situation further, Jack found that, each time the set was switched on, the capacitor was exposed to a brief surge

voltage of a magnitude some 50 per cent higher than the rated working voltage for this capacitor. This disclosure was especially annoying because Jack could easily have predicted the occurrence of this surge voltage if only he had known in the first place that surge voltages, even of infinitesimal duration, are liable to puncture the dielectric of a capacitor not suited to withstand them. To provide a capacitor capable of standing the surge voltage, it was now necessary to substitute a capacitor of substantially larger size on the already well-filled panel.

Fortunately, all these initial substitutions could be unobtrusively carried out without the matter coming to the attention of anyone of consequence, and the set performance was brought to a degree of perfection which drew the admiration of all—however, be it noted, all this came to pass under the equable conditions of the laboratory bench.

Now, it happened that this set was destined to roam far and wide in a truck as a part of mobile electronic equipment. Presently winter came and, each day as the temperature dropped, the performance of the set became noticeably poorer, until one very cold day it stopped altogether. Extensive tests in bitter cold disclosed the curious fact that an electrolytic capacitor marked 8 mf actually registered only 5 mf. This is one of the things that can happen to electrolytic capacitors when they are very cold. Now the circuit design clearly required a capacitance value of not less than 7 mf. Here, indeed, was a dilemma, because the impregnated paper capacitor capable of giving the desired capacitance value at low temperatures and which should have been used in the first place, was much too large to be accommodated in the small space originally, if rashly, assigned to the electrolytic capacitor. The record is obscure as to what was done about this.

In the next scene we have passed through the rising warmth of spring to the sizzling heat of summer. The time is late August and, lying in the blistering sun on midwestern plains, our set has now operated for many days in ambient temperatures reaching 130° F. Inside the set this ambient

heat, fed by more heat generated by the tubes and transformers, has skyrocketed the temperature to 180° F. Naturally, to meet the insistent demand of modern apparatus standards, the utmost in power had been squeezed into the minimum of space. Now the set went completely dead—an impregnated paper capacitor working under a most moderate direct voltage had become internally short-circuited.

This was indeed unexpected, because both slide rule and voltmeter showed positively that the voltage on this paper capacitor was well under the voltage-rating marked on the outside of the capacitor. On inquiry, Jack was surprised to learn that the combination of the voltage on this capacitor and the high temperature inside the set was sufficient to result in rapid deterioration of the dielectric in this type of capacitor. Should he have known this in the first place?

One day it came to pass that the truck moved down to the southern tip of Florida, where for days at a time the apparatus literally dripped with condensed water under the prevailing high humidity—and once again got out of order. It is, perhaps, a minor detail that ugly rust spots developed on the steel cases because the finish was not adequate for tropical conditions. More serious was the fact that moisture condensed to form leakage paths over inadequate insulation so that the performance of the set was seriously impaired. Worst of all is that moisture penetrated the seals of the capacitors, with fatal consequence. In the paper capacitors the dielectric had actually broken down under voltages which they could readily withstand in the absence of water. In the mica types, capacitance values had drifted beyond the precise limits needed for proper operation of the circuit. In brief, the capacitors failed for one reason or another because they were not suitable for operation under conditions of extreme humidity.

We can only conjecture what further mishaps might have overtaken this set, because at about this time the vice-president of the company again heard about it. The sequel is that the set was completely redesigned to employ capacitors actually

engineered to meet the varying operating conditions to which the set was exposed.

Now, were the capacitors to blame for these misfortunes? Is it reasonable to expect a capacitor, chosen at random from a catalog, to meet any and all possible combinations of operating conditions? Or was Jack to blame for lack of forethought? It is a fact that each and every one of these capacitor failures could have been avoided if Jack had had merely an elementary knowledge of the pitfalls of capacitor selection. It was not even necessary that Jack should know anything whatsoever about the specific characteristics of any of the capacitors in this set. All that was necessary was for him to find out what could happen to them under *all* the operating conditions.

This process of inquiry breaks down into asking the questions detailed at the end of book under "Twenty Keys to the Right Capacitor," Chap. 9. Naturally all of these questions do not apply to every capacitor application but collectively they provide a general dragnet for any capacitor problem. You may wish to turn to these questions now or you may prefer to read the remaining chapters first since they are intended to explain the reasons for the questions and to act as a guide as to how the questions should be answered in specific cases.

Once you have decided which questions apply to your problem and, having answered them, the next step is to make sure that the manufacturer is accurately and fully informed as to the capabilities the capacitor must have and the conditions under which it is to operate. The manufacturer can scarcely be blamed for an unsatisfactory capacitor if he did not know the operating conditions.

SUMMARY OF CHARACTERISTICS OF PRACTICAL CAPACITORS

In an ideal capacitor, the only factor to be considered would be the capacitance: pure, invariable and indestructible. In practice there are many additional factors, any of which can prove the undoing of a circuit if not properly taken into account. These considerations derive from limitations or characteristics which are inevitable in materials and in mechanical design; they are present in every capacitor no matter how well it was designed and built. There follows a summary of the factors of which we should be aware when we select and use capacitors.

1. *Capacitance Is a Variable.*

The capacitance value is never a constant. It changes when the frequency and the temperature change; it drifts gradually as the capacitor "ages" with the lapse of time. These variations are especially important in precision circuits.

2. *Capacitors Have Inductance.*

A capacitor behaves like a pure capacitance with a tiny coil in series. There is, therefore, a frequency at which it is self-resonant. Above this critical frequency, it behaves like a coil, which may be an important consideration in high-frequency circuits.

3. *Capacitors Have A-C Resistance.*

This is another way of saying that a capacitor dissipates energy in the form of heat. This loss must be strictly limited in high-power uses to avoid destructive heating and sometimes in low-power communication circuits to prevent objectionable impairment of transmission efficiency. It varies with both frequency and temperature.

4. *Capacitors Have Complex Impedances.*

Having inductance and resistance as well as capacitance, a capacitor exhibits a complex impedance. This may be capacitative in one range of frequencies, resistive in another and inductive in still another.

5. *Capacitors Take Time to Charge.*

Capacitors with solid dielectrics do not take in electric charge as rapidly as the charging source can supply it because the charging process is delayed by a lag in the response of the dielectric. For the same reason, such capacitors do not discharge instantaneously when short-circuited. This inherent delay, which differs widely in amount for different capacitor types, becomes important in special circuits where rapid response is essential.

6. *Capacitors Have D-C Leakage.*

Under direct voltage a fully-charged capacitor behaves like a conductor of very high resistance through which a current flows. This d-c leakage, although usually negligible from an operating standpoint, becomes significant in grid-plate coupling capacitors or in circuits required to have time constants of controlled magnitude. It varies greatly with temperature and the dielectric material (Fig. 33).

7. *Capacitors Wear Out.*

In general solid-dielectric capacitors deteriorate under electrical stress and are subject to failure in service even with apparently moderate voltages (or a-c currents) where this factor is not adequately taken into account by designer and user.

8. *Capacitors Need Protection.*

A capacitor must be constructed, housed, mounted and insulated so as to withstand its physical operating conditions, to endure, as the case may be, heat, humidity, vibration, shock, high altitude and fungus growth. This requirement, seemingly self-evident, is too often overlooked or under-estimated.

CHAPTER 1

How a Capacitor Behaves under Direct Voltage

How does a practical capacitor behave as an element in an electrical circuit? How is its behavior limited by its physical design and by the materials of which it is made? This chapter and the following one are intended to outline the essential—and inevitable—factors which control the performance of the capacitors with which we must work in designing and operating circuits. First step is their behavior under direct voltage.

Capacitance.

The forerunners of the present-day capacitor were thought of as devices for accumulating or isolating electrostatic charge. For example, charges generated by rubbing electrifiable substances such as glass or sealing wax could be imparted by successive increments to insulated conductors so as to build up a potential difference with respect to ground or to another insulated conductor. In general, the charge which could be isolated varied, depending on the size and shape of the conductors, the distance between them and the chemical composition and physical condition of the separating dielectric. The term "capacity" was used to describe the ability of a conductor-dielectric system to contain electrostatic charge. The preferred term is now "Capacitance."

Electrostatic or d-c capacitance (C) is defined as the ratio (Q/V) of the electric charge (Q) which the capacitor is capable of storing at the applied voltage (V). The practical unit of capacitance is the "farad," and that of electric charge, the "coulomb." The work done in charging the capacitor appears as stored potential energy, $\frac{1}{2}CV^2$, expressed practically in

watt-seconds. It is evident that capacitance is a measure of the charge or of the energy the capacitor can store under a given voltage. For example, a capacitor having a capacitance of one farad is capable of storing one coulomb of charge or one-half watt-second of energy for one volt.

Dielectric Polarization.

Charging a capacitor is like stretching a spring. In stretching a spring we store potential energy which is released when the stretching force is removed. When we apply a direct voltage to the terminals of a capacitor we pump in potential electrical energy, which is subsequently released when we short-circuit the terminals. This is explained on the theory that the electric field in the electrode-dielectric system causes systematic displacement of bound or anchored electric charges from the normal condition of equilibrium they occupy when the applied voltage is zero. This behavior contrasts with that of conductors in which the flow of current is explained as the drift of more or less free charges in the direction of the applied force. Each bound charge acts as though it were attached to its zero-voltage position by a spring. As the capacitor charges, the spring stretches under the force exerted by the electric field. On removal of the stretching force the charge returns to its normal position.

This condition of electric strain is known as "dielectric polarization," and the current which flows in the electrodes when the condition of strain is changing is known as the "polarization current." This current falls to zero when the polarization is complete and reappears in the opposite direction during the discharging process.

The total polarization which can occur per volt of applied potential between the electrodes depends on the total number of displaceable charges, their magnitudes and the average displacement of which they are capable in the direction of the applied field. Now the charge stored is proportional to the polarization. So capacitance, which is proportional to the charge per volt, is therefore also proportional to the polariza-

tion per volt of which the electrode-dielectric structure is inherently capable.

More generally the actual polarization occurring depends not only on the capacitance but also on the displacing force and therefore on the magnitude of the voltage applied to the capacitance. The work done in displacing the charges against the spring-like forces which tend to restore them to their original position appears as potential energy stored in the electrode-dielectric structure.

Capacitance and Dielectric Constant.

Consider a capacitor consisting simply of two parallel plates separated by air and having a capacitance C. In this case, assuming the air to be practically free of polarizable charges, the process may be pictured as limited to displacement in opposite directions of the positive and negative charges in the electrodes. With air as the dielectric the capacitance value obtained is the smallest realizable for a given plate separation and area (ignoring the very slightly smaller value obtainable in a vacuum). This value is increased by inserting any solid or liquid insulator between the plates.

If we completely fill the air space between the plates with a material of dielectric constant K the capacitance increases to KC and the stored energy to $(KC/2)V^2$. This increase in capacitance and energy is associated with the polarization introduced by the material dielectric. Thus the dielectric constant of the material is the factor by which the capacitance of an air capacitor is multiplied when we completely fill the air space with the material dielectric. The capacitor is capable of K times as much polarization, that is, of storing K times as much charge or energy for one volt as was realizable with air as the dielectric.

Evidently the larger the dielectric constant the larger the capacitance which can be realized in a given space. For this reason, materials of high dielectric constant are favored in practical design where it is necessary to conserve space.

Dielectric Absorption.

The total polarization taking place in a practical capacitor also depends on the period of time under the charging voltage. If we momentarily discharge a well-insulated impregnated paper capacitor which has been under direct potential for some time and then leave it on open circuit, it gradually accumulates a new charge in the electrodes, although the voltage reached is less than the original voltage. In high-voltage paper capacitors this absorbed or residual charge may be so large and therefore hazardous that it is found advisable to short-circuit the terminals of capacitors for several hours following the application of high voltage even for brief periods. The capacitor behaves as though a charge were "absorbed" by the dielectric and subsequently released gradually. This behavior, known as "dielectric absorption," is present in varying amounts in all solid-dielectric capacitors.

Dielectric absorption is significant from an operating standpoint because it causes the capacitance value to decrease with increasing frequency, which is an important consideration in precision-type capacitors. Also, the delayed charge and discharge may seriously degrade performance in circuits where the capacitor is required to discharge completely in a small fraction of a second.

Dielectric absorption is explained by the assumption that a finite time is required to displace the charges in the electric field. A lucid discussion of the process is given in a publication by Murphy and Morgan.[1] Just as time is required to stretch a spring, depending on the period of free oscillation of the spring, so a finite time is required to effect displacement of the bound charges in a dielectric, depending on the period of free oscillation of the charges with respect to their normal position under zero electric field and on the viscous forces which resist motion. In general, practical dielectrics contain different types of polarizable elements having different polarization times.

The fastest type of polarization consists of the displacement of electrons within atoms; displacement is completed in

about 10^{-15} second. This type of polarization is for practical purposes instantaneous as gauged by the requirements of present-day circuits. Requiring a longer period but still practically instantaneous is the type which arises from the displacement of charged atoms or ions within the encompassing framework of molecules.

Relatively slow-forming polarizations arise from molecules having an inherently unsymmetrical distribution of electric charges. Such molecules rotate so as to align themselves with the direction of the externally applied electric field, just as a compass needle rotates to conform to a magnetic field. Some rotate rapidly; others require many hours. Another type of slow-forming polarization arises in dielectrics made of materials having different dielectric constants such as impregnated paper which consists of paper, itself complex, plus an impregnating material which may also be complex. Resistance to motion encountered at the bounding or interfacial surfaces between the different materials retards the displacement of charges.

There is a wide variation in the polarization times not only among different types of polarizations but also among the individual polarizations of the same type, ranging from a small fraction of a second to many hours. The relative effect of instantaneous and slow-forming polarizations, for a well-dried, impregnated paper capacitor using best quality commercial materials, may be seen from the current-time charging curve in Fig. 1.

When direct potential is applied to a capacitor there is a large initial surge of charging or polarization current which in an absorption-free capacitor dies off asymptotically to zero in accordance with the relation,

$$I = \frac{V}{R} e^{-\frac{T}{CR}}$$

where V = the applied voltage, R = resistance in series with the capacitor and I = the current flowing after a time T. A capacitor capable of zero-time polarization charges at a rate

limited only by the value of R. With R = zero, the charging process would be instantaneous. In the test for Fig. 1, the value of R was made large so that the diminishing charging

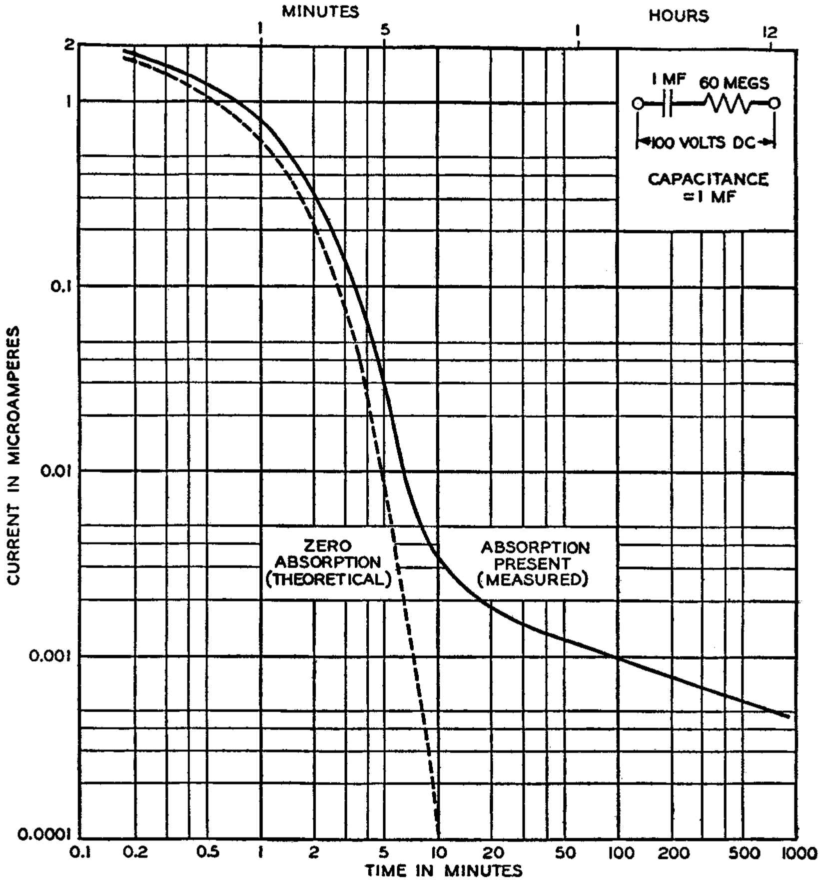


FIG. 1. Charging current versus time of direct-voltage application for paper capacitor.

current could be conveniently followed on a galvanometer. With this value of R the capacitor, if absorption-free, would be more than 99.99 per cent charged at the end of 10 minutes. Actually, due to the delaying effect of slow-forming polarizations, a polarizing current large enough to detect on the simple test circuit used was still flowing at the end of 24 hours of con-

tinuously applied voltage.* Evidently the time required to charge a practical capacitor depends only partly on the time constant of the charging circuit; it also depends on the time required to produce a response in the dielectric.

Dielectric absorption in any capacitor may be conveniently represented (as in Fig. 2) by a capacitor C_p having slow-form-

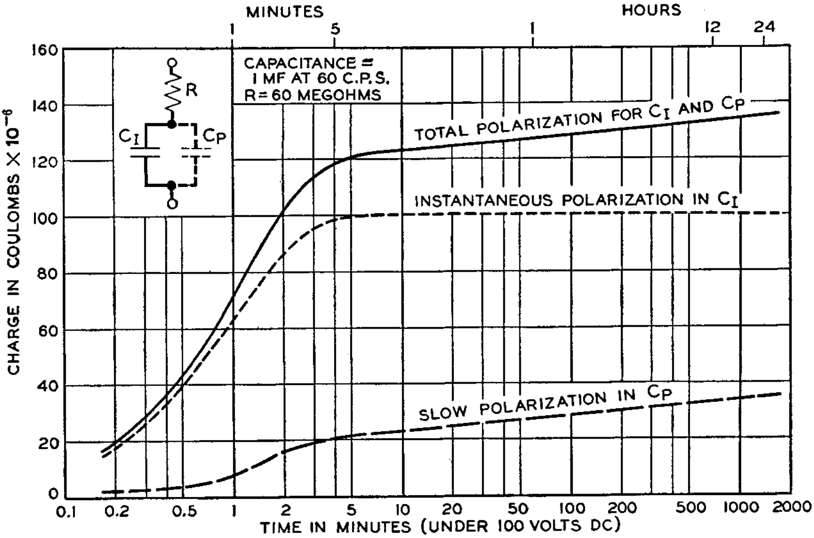


FIG. 2. Charge stored versus duration of direct-voltage application for paper capacitor.

ing polarizations in parallel with another capacitor C_I having instantaneous polarization. When direct voltage is applied, the capacitor C_I charges at a rate limited only by the series resistance (R). In contrast, the absorptive component C_p accumulates charge only as rapidly as the dielectric is capable of responding to the electric field. During the initial charging period required for C_I, C_p charges only in proportion, as it has polarizable elements whose periods are comparable with this

* In practical capacitors, the charging current gradually approaches a constant value which represents the leakage current through the dielectric and over and through terminals and other external insulation. Such leakage usually behaves like a conductance in parallel with the capacitor electrodes and does not influence the polarization.

period. For R = zero, the charging time for C_I would be instantaneous so that no polarizations would have time to form in C_p, and the capacitance appearing across the capacitor terminals would be equal to C_I.

Fig. 2 shows the growth of charge for C_I, C_p and $C_I + C_p$ for the capacitor of Fig. 1, over a 24-hour period. Following the initial charging period required for C_I, C_p continued gradually to "absorb" charge, increasing its contribution to the apparent capacitance as the various polarizations proceeded, a process which was still continuing at the end of 24 hours.

Reference

[1] "The Dielectric Properties of Insulating Materials," E. J. Murphy and S. O. Morgan, *Bell Sys. Tech. Jl.,* Vol. 16, pp. 493–512, Oct., 1937.

CHAPTER 2

How a Capacitor Behaves under Alternating Voltage

Capacitance Versus Frequency.

The behavior of a capacitor under periodically alternating voltage follows logically from its behavior under direct voltage. As the voltage alternates, a direct potential is applied first in one direction during one half-cycle and in the reverse direction during the succeeding half-cycle. The dielectric is rapidly flexed or strained to and fro in step with the alternating electric stress. The amount of polarization per volt depends on the duration of the half-cycle and therefore on the frequency.

How the amount of polarization called into play depends on the frequency is pictured schematically in Fig. 3 which shows three different polarization times, (a), (b) and (c), compared with the period of a low-frequency, and with that of a high-frequency alternating applied voltage. At the lower frequency, the half period is so long, compared with the three polarizations (a), (b) and (c), that every one of them can be completed even before the voltage passes through maximum during the half-cycle. In contrast, at the high frequency illustrated, only the rapid polarization (a) has time to reach completion; the slower polarizations (b) and (c) are still on the way, so to speak, when the voltage reverses.

Thus, as the frequency rises, a smaller and smaller proportion of the slower polarizations is called into play. At sufficiently high frequencies only the polarizations which are virtually instantaneous respond fully during each half-cycle. The practical outcome is that the apparent or measured capacitance decreases with rising frequency.

The measured increase in capacitance with duration of voltage application for a mineral oil impregnated, paper capacitor is shown in Fig. 4. Apparently, 35 per cent more

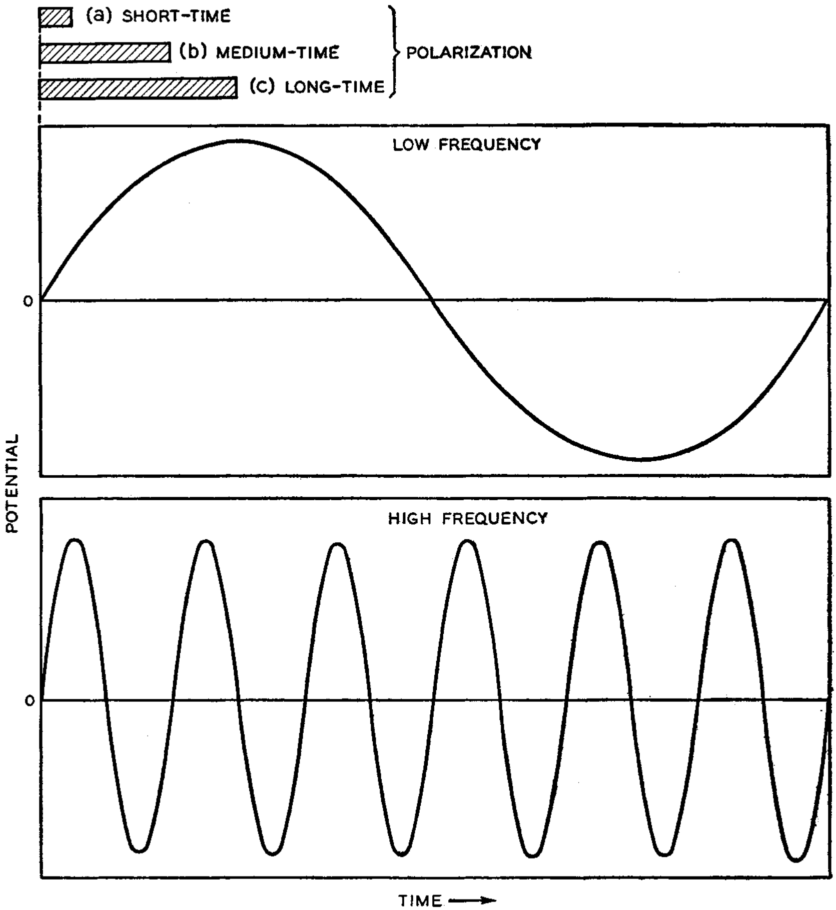


FIG. 3. Polarization-time for bound charges in a dielectric compared with half-period of alternating applied voltage. At higher frequencies, the potential reverses direction before completion of longer-time polarizations so that capacitance decreases with rising frequency (see Fig. 4).

polarization (that is, capacitance) is called into play when the voltage is applied in one direction for 24 hours than when it alternates at the rapid rate of 500 kc. However, the greater

part of this polarization is inactive for times less than 0.008 second corresponding to 60 cycles per second and is therefore usually not of practical significance. Evidently due to the time-dependence of capacitance in practical capacitors, a precision a-c capacitance value must be defined with reference to

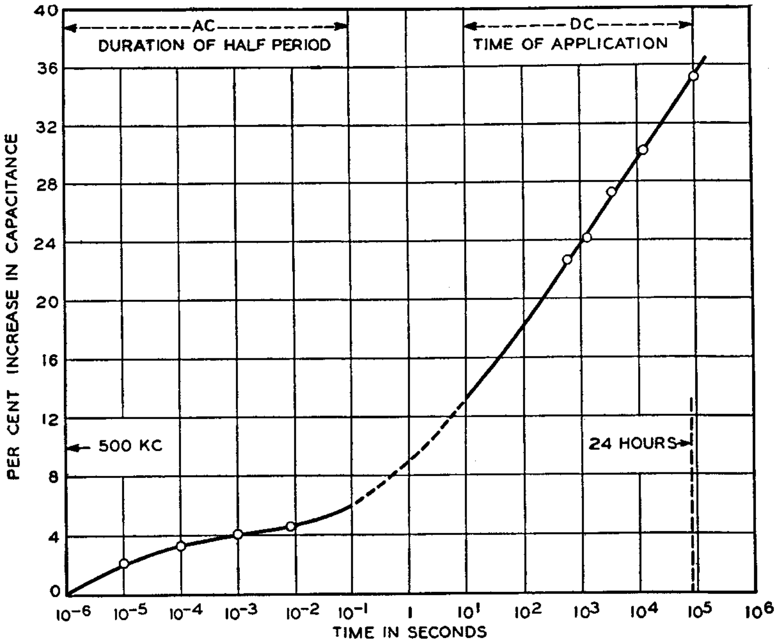


FIG. 4. Capacitance versus duration of voltage-application for paper capacitor.

a specific frequency, and d-c capacitance on the basis of a given time of voltage application. What is sometimes referred to as the "zero-frequency" capacitance value, corresponding to infinitely long voltage application, has no practical significance apart from the fact that no one could live quite long enough to measure it.

The Impedance of a Capacitor.

For a-c operation we are interested in the rate at which a capacitor handles electric energy and the efficiency with which

it does this. Each time the capacitor is charged or discharged a current flows in the electrodes and connecting leads. Evidently, the more quickly the capacitor is put through this charge and discharge process, the larger the total charge flowing per unit time, that is, the larger the effective current. Under alternating voltage, the capacitor is charged once and discharged once during each half-cycle, and the current therefore increases as the frequency rises.

The current flowing through a capacitance (C) under an r.m.s. voltage (E) at a frequency (f) is $2\pi fCE$, and the corresponding reactive power is $2\pi fCE^2$. The factor $-1/2\pi fC$, known as the "reactance," is a measure of the total charge or energy entering and leaving the capacitor per unit voltage in unit time. From a circuit or transmission network standpoint, a capacitor appears simply as a means of supplying negative reactance.

The impedance of the ideal capacitor would be only negative reactance; that is, it could absorb energy from an applied source of power and return all of it to the source without loss. In practice there is an energy loss in the dielectric and another one as the current flows in the electrodes and connecting leads. A capacitor also has some inductance which, however small, results in inductive or positive reactance the magnitude of which increases with rising frequency. Above some critical frequency, depending on the type of capacitor, the inductive reactance may dominate and the capacitor then behaves like an inductor.

Thus a capacitor behaves like a two-terminal network consisting of pure capacitance, inductance and resistance. Therefore the impedance appearing across the terminals is complex and expressible in the form $R \pm jX$, where R denotes the resistance and X the reactance.

In many applications, usually for low frequencies, the magnitude of the inductance and resistance are negligibly small compared with that of the inductance and resistance of the circuit in which the capacitor is used. In other applications, usually at higher frequencies, the reduction of unwanted in-

ductance and resistance to sufficiently small amounts may constitute a difficult design problem.

The way in which inductance and resistance enter into practical capacitors may be seen from Fig. 5. In Fig. 5 (a) the electrodes, dielectric and electrode connections are shown diagrammatically. The circuit behavior of this structure may be

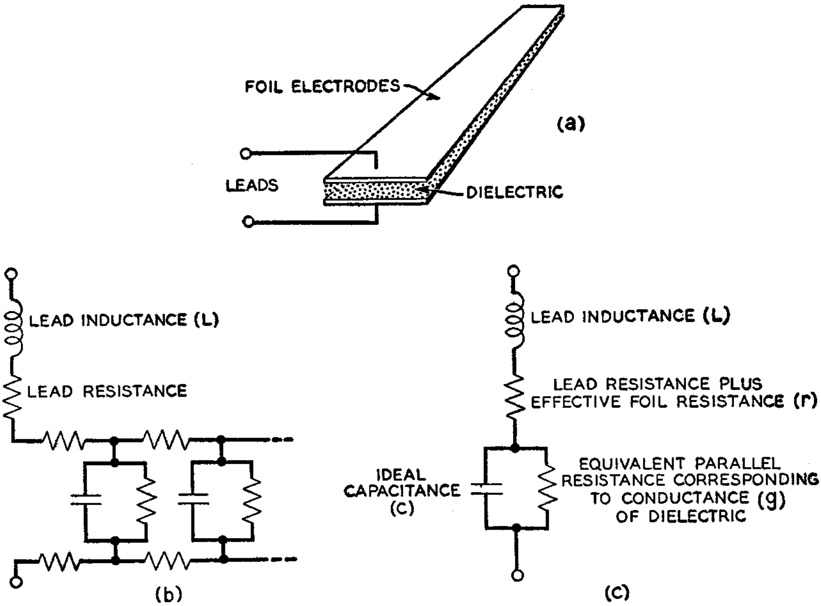


FIG. 5. Equivalent electrical circuit of a capacitor.

represented by that of the equivalent two-terminal network shown in Fig. 5 (b). The impedance of this network is made up of the inductance and resistance of the leads plus the impendance inherent in the unit apart from the leads. In practice the inductance of the unit by itself is usually negligibly small compared with the other factors which determine the impedance. The inductance of a capacitor is approximately that of a wire loop equal in area to that formed by the two leads and the unit. Looking along the foils from the direction of the lead-in connections the structure appears electrically as a network consisting of uniformly distributed series re-

sistance and shunt capacitance and conductance. This resistance is associated with the electrodes, and the shunt conductance with the dielectric. The network in Fig. 5 (b) reduces to the equivalent network shown in Fig. 5 (c). The impedance "Z" of this network is given by

$$Z = r + \frac{g}{g^2 + \omega^2 C^2} - j\,\frac{\omega C}{g^2 + \omega^2 C^2} + j\omega L. \qquad (1)$$

In practice g^2 is small compared with $\omega^2 C^2$. Equation (1) therefore reduces to:

$$Z = r + \frac{g}{\omega^2 C^2} + j\left(-\frac{1}{\omega C} + \omega L\right). \qquad (2)$$

where $\omega = 2\pi$ frequency.

The effects of parasitic resistance and inductance on the impedance of a 1-mf paper capacitor designed for audio-frequency operation are illustrated in Fig. 6. In an ideal capacitor the impedance appearing across the terminals would be $-1/\omega C$ at all frequencies. In a practical capacitor, the capacitance forms with the inductance a series circuit. Consequently the positive reactance associated with the inductance (L) reduces the negative reactance appearing across the terminals by an amount equal to ωL. The effect of this inductive element is, therefore, to increase the apparent capacitance as the frequency rises. It is also to be noted that this inductive effect is opposite to that of dielectric absorption which causes a reduction in capacitance with rising frequency.

In general the measured or effective capacitance C_e appearing across the capacitor terminals is given by $C_e = C/(1 - \omega^2 LC)$. At low frequencies the reactance of a capacitor usually approximates the ideal value $(-1/C\omega)$ and the effect of (L) is negligible until the higher frequencies are reached. The inductive effect increases with frequency and, for the particular example covered in Fig. 6, becomes large above 100 kc.

In the region of the resonance frequency, where the reactance changes from negative to positive, the impedance of

the capacitor is controlled by the effective resistance. For this reason the magnitude of the effective resistance may be the prime consideration in the design of by-pass capacitors which are required to have low impedances at high frequencies.

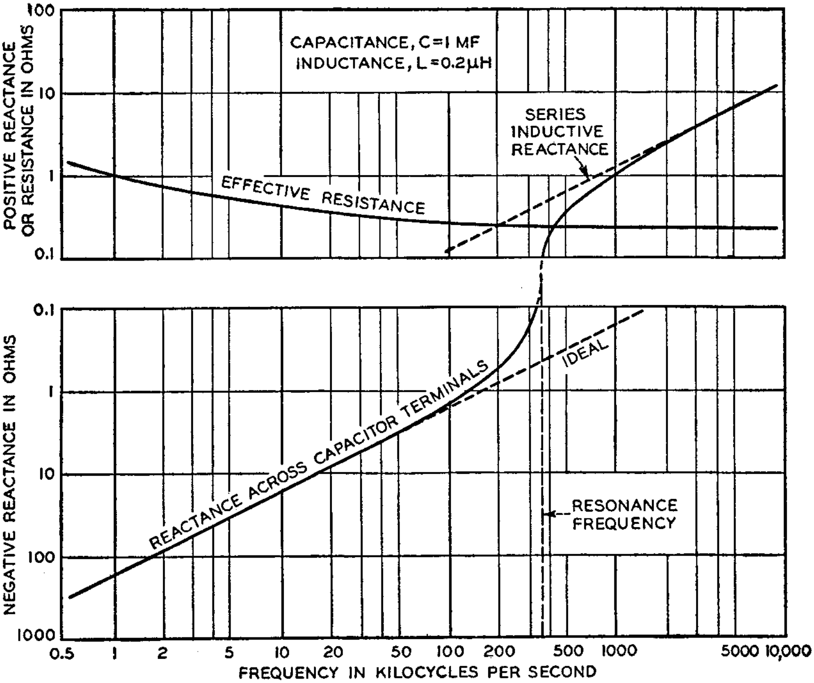


FIG. 6. Impedance versus frequency for wax-paper capacitor designed for audio frequencies.

Above the resonance frequency the reactance becomes positive so that the capacitor behaves like a coil with a series capacitance. Every capacitor of conventional design will eventually resonate if the frequency is carried high enough. However, in capacitors designed for high-frequency use the values of C and L are usually such that resonance occurs at much higher frequencies than that shown in Fig. 6. It is possible to arrange the electrodes and terminal connections to obtain the effect of a low-impedance, long transmission line free of ap-

parent resonance over a very wide high-frequency transmission band.

The Effective Resistance and Heat Loss.

The effective resistance of a capacitor causes its impedance to deviate from a pure reactance and is associated with the generation of heat.

The current is E/Z for an applied voltage E. Except at frequencies approaching resonance, the current is approximately equal to $E\omega C$. Then using the expression for the effective resistance from Eqn. 2, the heat loss is given by:

$$E^2\omega^2C^2\left(r + \frac{g}{\omega^2C^2}\right) = E^2\omega^2C^2r + E^2g. \tag{3}$$

The first term represents loss in the foil and leads, and the second term, loss in the dielectric.

In capacitors required to carry large currents the energy dissipation is a source of heating which, if not adequately reduced or dissipated by thermal conduction, may cause rapid deterioration and failure of the dielectric. Consideration of heat loss enters into the design and use of capacitors for low-frequency operation in connection with power factor correction and, at high frequencies, in radio transmitting capacitors. In radio circuits, effective resistance becomes important in series coil and capacitor combinations required to have low impedance at the resonance frequencies or parallel combinations required to have high impedance at the anti-resonance frequency. This is because resistance may add appreciably to the desired low impedance at the resonance frequency or reduce the desired high impedance at the anti-resonant frequency.

In electric wave filters intended to pass one band of frequencies and suppress another, the transmission loss is ideally zero over the pass-band and rises sharply beyond the edge or edges. Parasitic dissipation in the reactive elements introduces unwanted loss which varies over the pass-band and reaches a maximum at the edges resulting in distorted trans-

mission. This source of loss may be seriously objectionable, for example, in carrier-telephone systems where the cumulative loss of many filters in tandem may result in considerable distortion which must be compensated for by means of attenuation-equalizing networks.

In his efforts to limit the losses in capacitors required to pass alternating current in telephone and electronic circuits, the capacitor engineer is usually primarily concerned with the effect of frequency. This is because the effective resistance undergoes large changes with changing frequency and because of the wide frequency-range such circuits are often required to cover. Consequently special attention is given to the effect of frequency in the following discussion of the factors which control effective resistance.

It is also assumed that the effective resistance is independent of the applied voltage. For practical purposes, any changes in effective resistance with rising voltage are usually unimportant up to the corona voltage. At this point, air between electrodes and leads, air or gas trapped in the dielectric or even the dielectric material itself starts to ionize—that is, electrons are liberated. Gathering velocity in the electric field, these electrons collide with atoms and molecules to knock out more electrons. This cumulative process produces electric current of greater intensity than the dielectric can stand without disintegrating or literally burning up. Above the corona voltage point the effective resistance not only becomes unstable in value but also usually undergoes large increases with further increases in voltage. Capacitors should be rated to operate at voltages well under the corona point, and in this discussion corona is assumed to be absent.

Loss in Foil and Leads.

As a first approximation the effective resistance of the foil and leads of a capacitor is usually a constant over a wide range of frequency. At higher frequencies, the value increases due to eddy-current and other losses. However, since in the ma-

jority of capacitors, these high-frequency effects do not enter appreciably, they are not discussed in detail.

Then, if we assume that the effective resistance r is constant, from Eq. 3, we have:

$$\text{Heat loss in foil and leads} = E^2\omega^2C^2r = E^2(2\pi C)^2rf^2.$$

On this basis the heat loss in the foil and leads increases as the square of the frequency for constant applied voltage. In general, this condition applies over the operating frequency-range of paper capacitors.

In the case of wound paper capacitors, there is a simple relationship between the effective resistance of the foil electrodes and their d-c resistance. With reference to Fig. 5 (a), it may be shown that alternating current entering the foil electrodes at the lead-in wires decreases as it spreads along the foils, and the current flowing at points remote from the lead-in wires may be only a small fraction of the entering current. It may be shown theoretically and demonstrated experimentally that for the long, narrow electrodes of wound paper capacitors the effective foil resistance is approximately equal to ⅓ of the loop d-c resistance obtained by adding the d-c resistance values of the two foils. In other words, due to current attenuation along the foils only 33 per cent of the total d-c foil resistance is effective with respect to alternating current.

Where, as is more usual in practice, the terminals are laid in at approximately the middle of the foil electrodes, the current spreads in opposite directions along the foils. The effective resistance of the loop in each direction is then $R/6$ and, since the two loops are in parallel, the total effective resistance becomes $R/12$.

In practical design this is a useful relationship in evaluating the effective resistance of wound paper capacitors.

Dielectric Loss.

Just as some energy is lost as heat in stretching a spring, so energy is lost in a practical dielectric as work done against

frictional resistance to the displacement of electric charges. For a detailed discussion of the process, reference may be made to a publication by Murphy and Morgan.[1]

We may visualize the process by considering a bound charge which is fully displaced during each half-cycle. If the applied voltage is constant the displacement will also be constant. Also the time during which the charge moves is a constant since it depends solely on the natural vibration-period of the charge. Consequently, the amount of work (W) done against friction each time the charge is displaced is a constant. During the first half-cycle an amount of work (W) is done against friction and an equal amount is done in the subsequent half-cycle when the voltage reverses. Consequently the total work done during the complete cycle is $2W$. If we double the frequency the total work done in the same time becomes $4W$, and $6W$ if we triple the frequency. In other words, for constant applied voltage, the rate of work done against friction, that is, the energy dissipated in heat, increases in proportion to the first power of frequency.

As we continue to raise the frequency a point is reached where the bound charge does not have time to undergo complete displacement during each half-cycle. This means that the work done during the half-cycle will be less than W. Thus, as we carry the frequency still higher less work is done in moving the bound charge against friction during each half-cycle but, on the other hand, the motion undergoes more frequent reversals. The net effect is that the heat loss increases more slowly after the frequency rises above this critical point. It eventually reaches a steady value independent of frequency.[1] In general, dielectric loss varies with frequency in a more complicated manner than herein described since it depends on the cumulative effect of different types of polarization.

According to Eqn. (3) the dielectric loss, being given by E^2g is, for constant voltage, proportional to "g." On the basis of dielectric theory, the dielectric conductance "g" increases with rising frequency for all materials. For mica, glass and certain waxes, MacLeod[2] found that g varies as

f^n, where n is positive. This relationship is also found to apply to impregnated paper capacitors, under low voltages, at room temperature and over the limited frequency ranges studied. In symbols:

$$g = g_0 f^n, \tag{4}$$

where g_0 and n are constants.

From Eqn. (2), the total effective resistance (R) of the capacitor is given by:

$$R = r + \frac{g}{\omega^2 C^2}.$$

Substituting Eqn. (4), we then have:

$$R = r + \frac{g_0 f^{n-2}}{(2\pi C)^2}.$$

In Fig. 7, this expression is shown plotted for a wax-impregnated paper capacitor for which the value of "n" is found empirically to be 1.35. In this case $n - 2$ is negative so that the $g_0 f^{n-2}/(2\pi C)^2$ decreases with rising frequency.

Broadly speaking, the effective resistance of capacitors is controlled by the dielectric at low frequencies and by the electrodes and leads at higher frequencies.

We may note that although the conductance "g" of the dielectric increases with rising frequency, the contribution which it makes to the effective resistance of the capacitor decreases. So the higher the frequency, the less the effect of the dielectric on the effective resistance. This can also be seen from Fig. 5 (c) in which the reactance of the capacitance $1/2\pi fC$ may be regarded as a shunt across the conductance "g." As the frequency rises, the value of this reactance decreases so that its shunting action on the conductance is greater.

Assuming $n = 1.35$, the heat loss in the dielectric $= E^2 g = E^2 g_0 f^{1.35}$; thus, for constant voltage (E), the dielectric heat loss in the capacitor under consideration, like the foil loss, also increases with rising frequency but in proportion to the 1.35 power of the frequency over the frequency-range covered.

The comparative increases in foil and dielectric losses with rising frequency are shown for constant voltage in Fig. 8 and for constant current in Fig. 9 (for capacitor in Fig. 7).

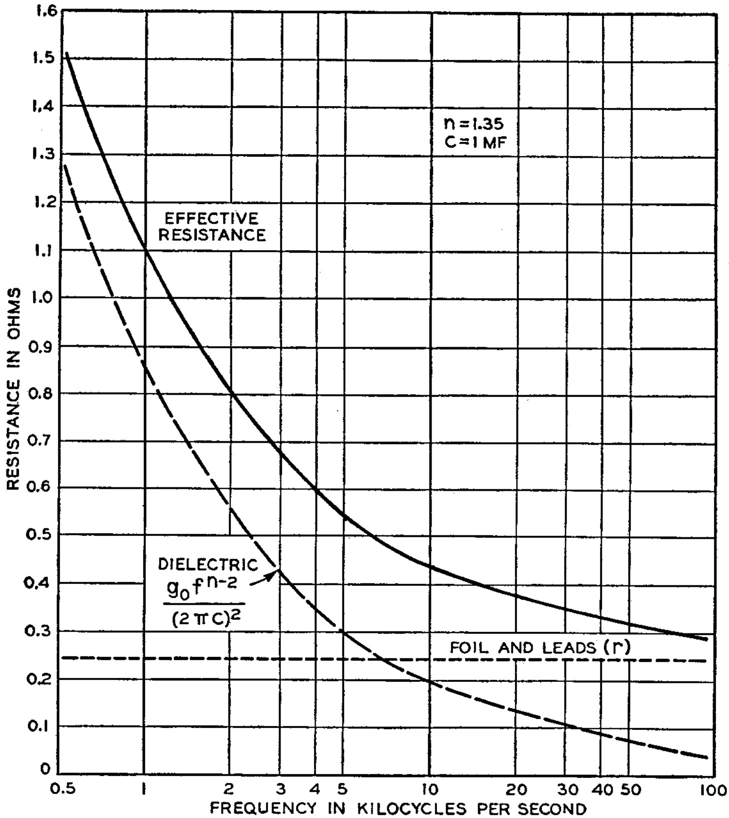


FIG. 7. Effective resistance versus frequency for wax-paper capacitor designed for audio frequencies. Both dielectric and foil contribute to effective resistance.

With reference to Fig. 8 the practical significance is that a capacitor rated to operate under a given a-c voltage at a given frequency without overheating may seriously overheat under an equal voltage at a higher frequency due to the increase in both dielectric and foil loss.

With reference to Fig. 9 the practical significance is that a capacitor which is rated to carry a given current at a given

frequency without overheating may seriously overheat with an equal current at a lower frequency due to the increase in dielectric loss.

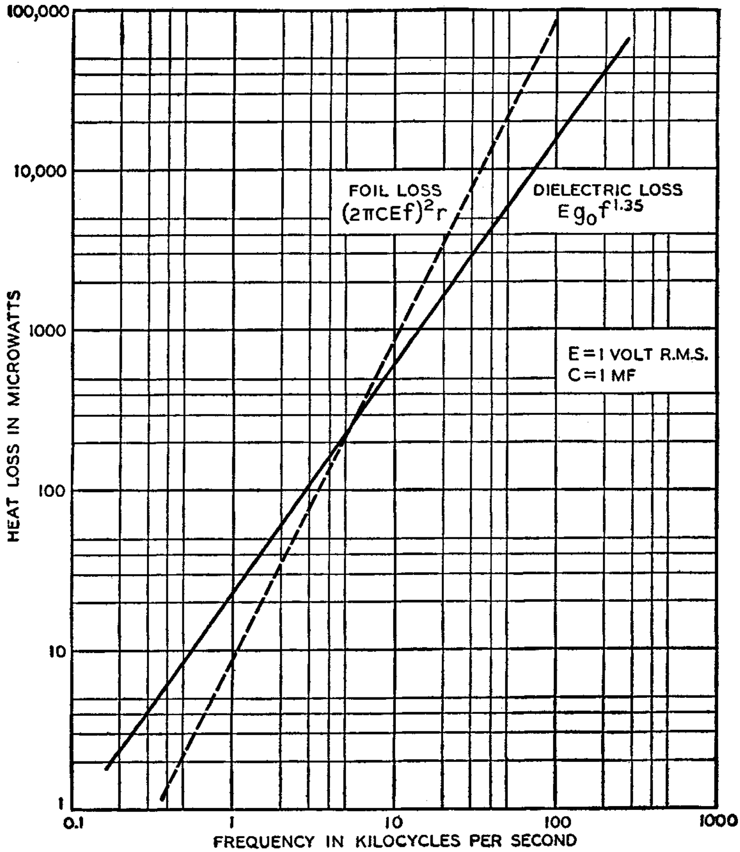


FIG. 8. Heat loss versus frequency for constant voltage in wax-paper capacitor.

On the other hand, it is not conversely true that equal currents may always be safely carried at higher frequencies because additional losses may enter due to eddy current and other effects in the electrodes, leads, metal terminals and bushings. For constant current these high-frequency losses increase as the frequency rises. Since these losses are closely dependent on the mechanical design of the capacitor, their

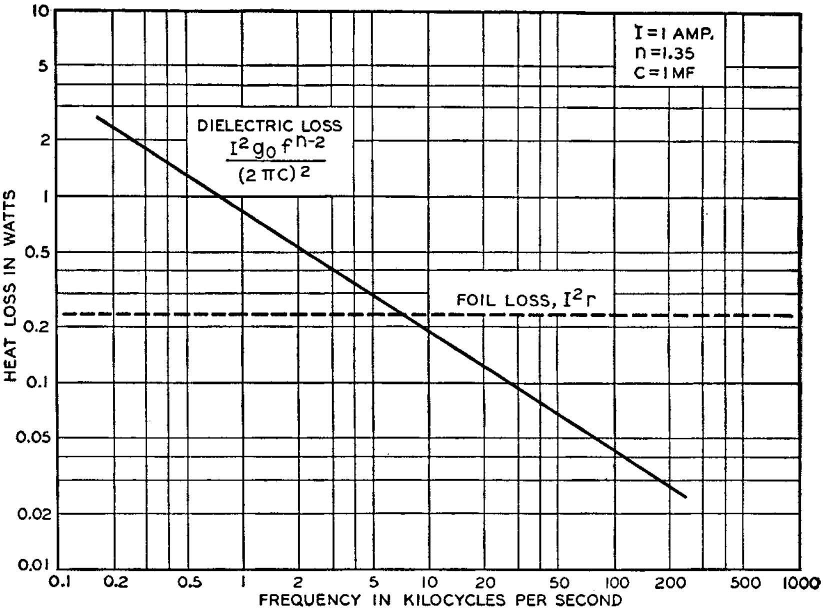


FIG. 9. Heat loss versus frequency for constant current in wax-paper capacitor.

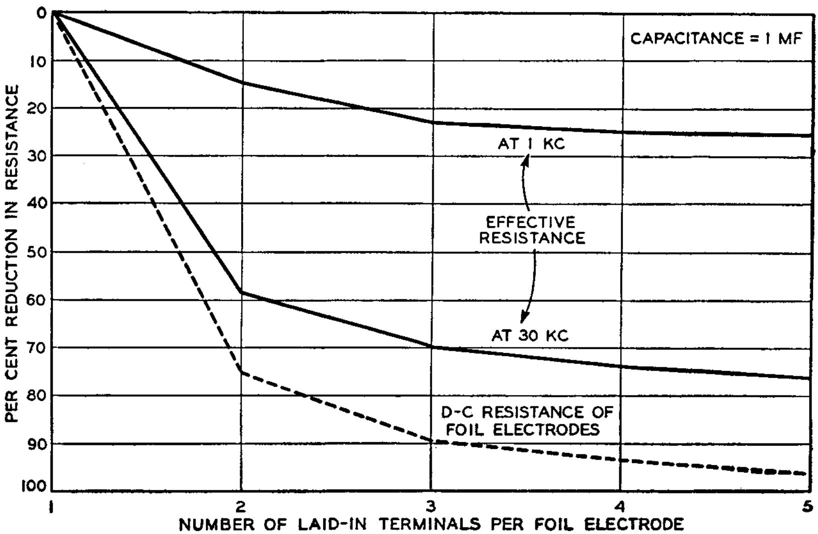


FIG. 10. Effective resistance is reduced by adding terminals, especially at higher frequencies.

magnitude is usually difficult to compute theoretically and in practice they are determined by direct test on specific designs.

Reduction of Foil Loss.

With a dielectric of given material, area and thickness, little can be done to improve the dielectric loss. However, much may be done to improve the foil loss by controlling the d-c resistance of the foils and connecting leads. Foil loss is reduced by using metals of lower specific resistivity and by proportioning the dimensions so as to increase the thickness and the width relative to length. For foils of fixed dimensions the effective resistance may be greatly lessened by laying in more terminals at intervals along the foil and connecting the terminals together. When "n" terminals are laid in on a foil of length "L," it may be shown that the lowest resistance is obtained by spacing the terminals at intervals of L/n, with each end terminal located $L/2n$ from the end of the foil. With this arrangement the effective resistance is inversely proportional to the square of the number of terminals.

Fig. 10 illustrates the reduction in effective resistance at two frequencies due to increasing the number of terminals for a low-voltage, wax-impregnated paper capacitor. As the curves show, the reduction in the effective resistance R obtained with the multi-terminal construction is greater at the higher frequencies. This is because, at the higher frequencies, the value of the dielectric component g/ω^2C^2 becomes smaller relative to the foil resistance. Also the advantage gained by adding more terminals decreases as the total number of terminals increases. In the limiting case the edge of the foil is connected together along its entire length. This, known as "extended foil" or "overlapped foil" construction (see Fig. 22), gives the lowest attainable effective foil resistance for a foil of given material and dimensions. In addition, by providing an efficient conduction path for heat from the inside to the outside of the unit, extended foil construction is advantageous in high-power capacitors having large heat dissipation. In low-power capacitors the advantage of extended foil construction

over several laid-in terminals may be outweighed by manufacturing or design difficulties.

The "Q" of a Capacitor.

Where we are interested solely in heat generated, it is convenient to think in terms of the resistance or of the power factor since these are measures of the amount of heat dissipated. In precision, low-voltage, low-current wave filters and networks the dissipated energy is negligible from a heating standpoint, and we are interested in the impedance of a capacitor solely as approximating a pure reactance. For this purpose it is more convenient to think in terms of the ratio of reactance to effective resistance, defined as "Q."

The factor "Q" is a measure of the performance of a capacitor as compared with that of a pure reactance. The higher the "Q" the more nearly the resistance or dissipation approaches the ideal value of zero. The higher the "Q" of the reactive elements of an electric wave filter, the lower the attenuation in the pass-band and the sharper the attenuation cut-off at the edges.

From Eqns. (2) and (4) the "Q" of the capacitor (being defined as the ratio of reactance to resistance) is given by the following expression * (ignoring wL):

$$Q = \frac{1}{\dfrac{g}{\omega C} + r\omega C}$$

$$= \frac{1}{\dfrac{g_0 f^{n-1}}{2\pi C} + 2\pi C r f}. \tag{6}$$

* A capacitor may also be represented as a pure capacitance (C) in parallel with an effective conductance (G). Test bridges are usually set up to measure the quantity (G). In this case, $Q = \omega C/G$.

Capacitors, especially those intended solely for a-c use, are usually specified in terms of power factor. For purposes of approximate computation, it may be assumed that Q is equal to the reciprocal of the power factor. For $Q = 10$, the error in this approximation is only ½ per cent and is less for higher values of Q.

In Eqn. (6) the factor $\frac{g_0 f^{n-1}}{2\pi C}$ is associated with the dielectric loss while $2\pi Crf$ is associated with the foil loss. Evidently the value of Q at any frequency is inversely proportional to the sum of these two factors. The comparative effect of the

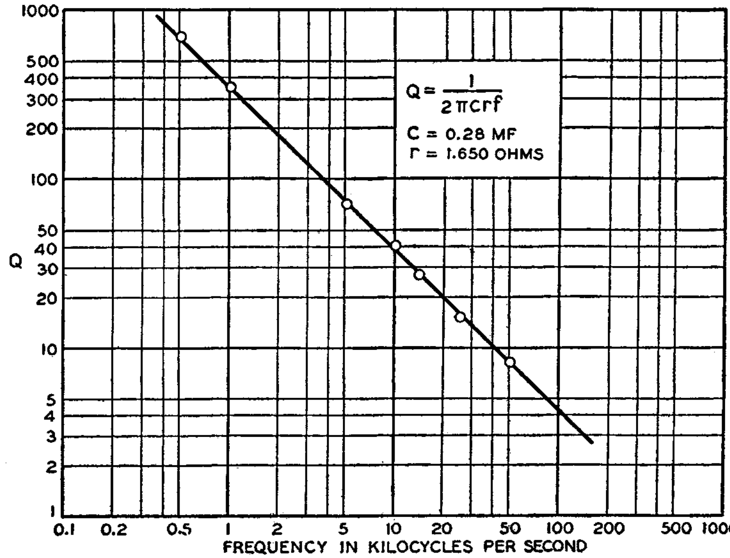


FIG. 11. Q versus frequency for polystyrene capacitor with foil loss dominant.

foil and dielectric factors on Q versus frequency are illustrated in Figs. 11, 12, 13 and 14.

Fig. 11 covers a polystyrene capacitor for which the dielectric factor is negligible compared with the foil factor which therefore controls the Q. Assuming $\frac{g_0 f^{n-1}}{2\pi C}$ = zero in Eqn. (6), then $Q = \frac{1}{2\pi Crf}$. Thus, Q is inversely proportional to the frequency.

Fig. 12 covers a paper capacitor for which the foil factor is negligible compared with the dielectric factor which therefore controls the Q. Assuming $2\pi Crf$ = zero, then

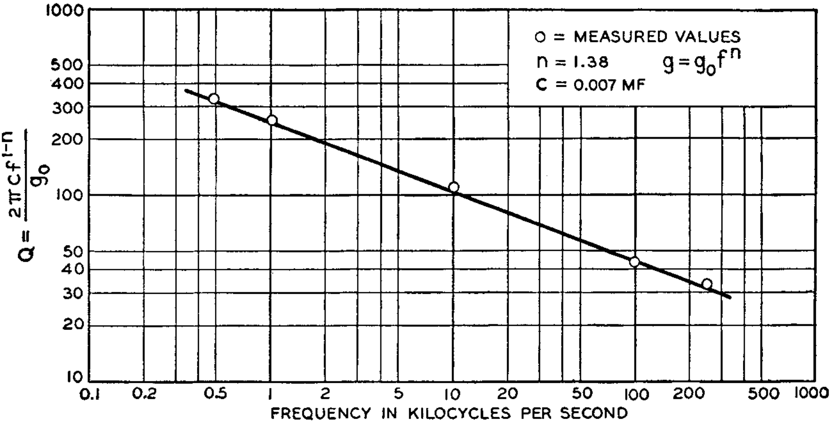


FIG. 12. Q versus frequency for tubular mineral-oil paper capacitor with dielectric loss dominant.

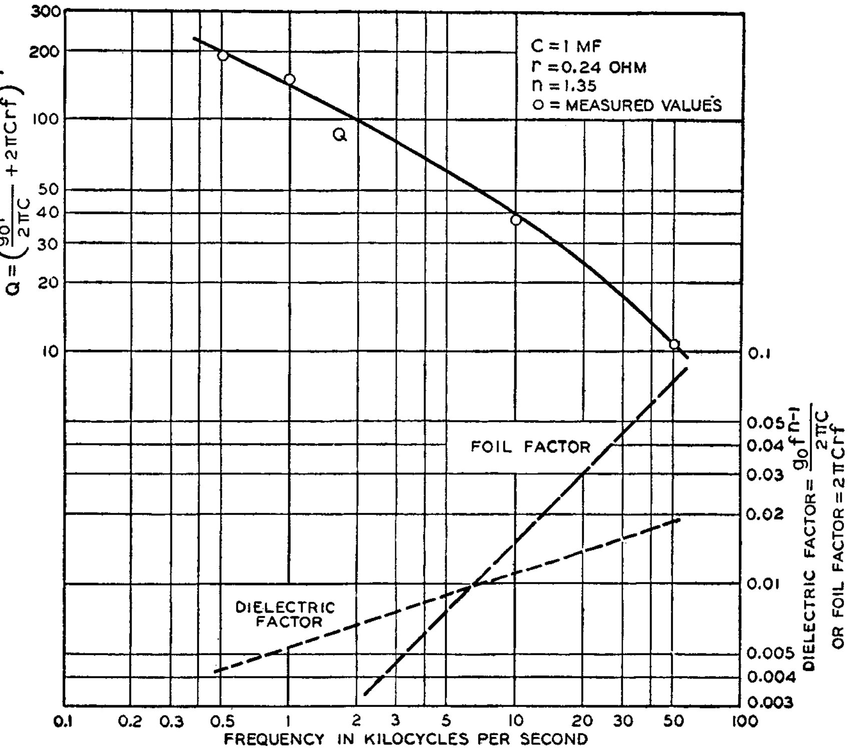


FIG. 13. Q versus frequency for paper-halowax-tinfoil capacitor designed for audio frequencies.

$Q = \frac{2\pi C}{g_0} f^{1-n}$. Since n is greater than unity, $1 - n$ is negative, so that Q decreases with rising frequency.

For the paper capacitor covered in Fig. 13, both dielectric

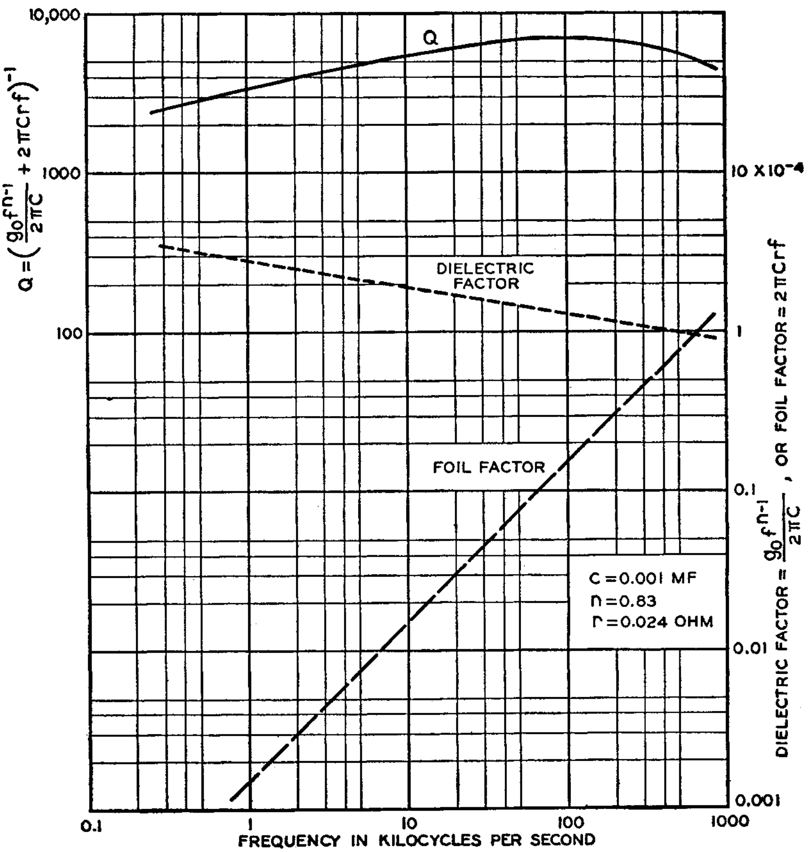


FIG. 14. Q versus frequency for silvered mica capacitor.

and foil factors control the Q. Also both factors increase with rising frequency so that the Q decreases. However, the dielectric factor has major control at the lower frequencies, and the foil factor at the higher frequencies.

For the mica capacitor covered in Fig. 14, n is less than unity so that $n - 1$ is negative and the dielectric factor de-

creases with rising frequency. Consequently at the lower frequencies, where the dielectric factor has major control, the Q rises with the frequency. At the higher frequencies, the foil factor becomes large enough to initiate a decrease in Q so that the curve passes through a maximum point.

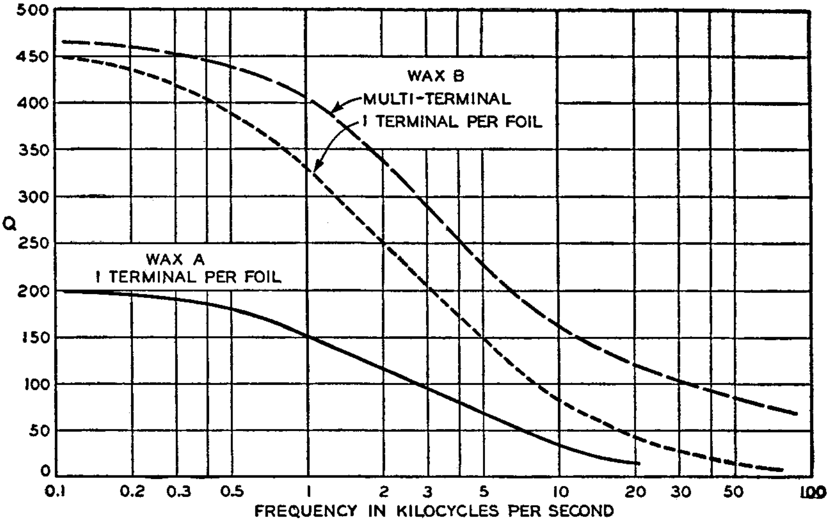


FIG. 15. Q versus frequency for wax-paper capacitor. Q is improved by using lower-loss wax and further improved by increasing number of foil-electrode terminals.

Fig. 15 shows the improvement in Q effected by changing from impregnating wax A to wax B which has lower dielectric loss. It also shows the further improvement effected by reduction in foil loss by increasing the number of foil terminals.

Summary.

When a capacitor charges under voltage, it acts somewhat like a contracting spring as the bound electric charges are "polarized"—that is, displaced from their normal positions of equilibrium.

Solid dielectric capacitors do not charge as rapidly as the charging source can supply energy because some of the polariz-

able charges react too slowly. Conversely, a capacitor does not wholly discharge at once when short-circuited. Capacitance, measure of total polarization or of charge stored, is therefore a function of duration of uni-directional voltage application.

This delay in polarization, known as "dielectric absorption," has two practical consequences. It can cause objectionable delay in circuits where rapid response to changing voltage is essential. It also affects the capacitance value on a-c. With alternating voltage, the capacitance exhibited depends on the amount of polarization that can be effected during each half cycle before the potential reverses (Fig. 3). Since the duration of the half cycle decreases with rising frequency, the polarization obtainable also decreases. So capacitance decreases as frequency rises.

Energy is dissipated as the bound charges move to and fro against frictional resistance and as the current flows in the electrodes and leads. The energy-dissipating element in the dielectric appears as a conductance across the electrodes, that of the electrodes and leads as a resistance in series (Fig. 5). Their combined effects constitute the effective resistance R of the capacitor. The impedance is therefore complex and given by $R - JX$ where X denotes the reactance.

The dielectric conductance itself increases with rising frequency (page 32) but it acts in shunt with the electrodes and contributes less to the total resistance (R) as the frequency rises. In contrast, the electrode and lead resistance remain approximately steady in value up to frequencies where they are augmented by effects peculiar to high frequencies. In general, therefore, capacitor losses are controlled mainly by the dielectric loss at low frequencies and by the electrode and lead losses at higher frequencies (Fig. 7).

In high-power circuits this energy loss limits the current-carrying capacity of capacitors; and in low-power precision circuits, such as wave filters, it limits the performance where a precise attenuation-frequency characteristic is needed.

The power factor is a convenient measure of capacitor ef-

ficiency in power circuits. However, in calculating low-power precision circuits, the Q (ratio of reactance to resistance) is often more convenient. Where the value of Q is 10 or more, it is equal to the reciprocal of the power factor within 0.5 per cent.

A small inductance (Fig. 5) inherent in the electrodes and leads, acting in series with the electrodes, causes the measured capacitance to increase with frequency—an effect opposite to that of dielectric absorption. Because of this inductance the capacitor series-resonates if the frequency is carried high enough (Fig. 6).

References

[1] "The Dielectric Properties of Insulating Materials III, Alternating and Direct Current Conductivity," E. J. Murphy and S. O. Morgan, *Bell Sys. Tech. Jl.,* Vol. 18, pp. 502–537, July, 1939.

[2] "The Variation with Frequency of the Power Loss in Dielectrics," H. J. MacLeod, *Phys. Rev.* (2), Vol. 21, Jan., 1923.

CHAPTER 3

Capacitors Wear Out

It is well known that capacitors are limited in their ability to withstand electrical potential and, if on alternating current, also to carry current. Less well recognized is that there may occur gradual changes—chemical, physical or even mechanical in nature—which reduce the ability of the capacitor to withstand electrical strain. Such changes may eventually lead to breakdown through or around the dielectric or between the terminals and the container inside or outside.

In some capacitor types, the durability is so great as to be for practical purposes infinite; in others deterioration may proceed so actively that the capacitor becomes useless after only a few months or even a few days of service. No capacitor type should ever be considered as exempt from wear especially where high voltage, high a-c current, high temperature or exacting physical conditions are involved.

It may occur to us that the simple way to avoid the hazard of failure would be to use enough insulation to meet and weather all possible hazards. In this, however, we are severely limited from a space standpoint by the insistent demand for smaller, more compact apparatus. And when we consider that merely doubling the dielectric thickness may quadruple the volume (for a fixed capacitance), we can readily see why capacitor engineers seek to make the dielectric as thin as possible as well as to reduce all other space-consuming insulation to a minimum.

In other words it may be necessary to work materials at close to the limit of their capabilities. However, this feat can be safely achieved only through the most careful design, testing and manufacture, so as capacitor users we must keep in

mind this ceaseless pressure on manufacturers to make capacitors as small as possible and to evaluate the possible implications of such space economy in terms of durability.

How long a capacitor is likely to endure under its operating conditions, electrical and physical, is always a "must" question regardless of the type involved. Obviously it becomes the most important question of all if there is any doubt whatsoever as to the ability of the capacitor to stand up.

Much study has been devoted to the endurance of solid dielectrics. This is not surprising when we consider the enormous area of thin dielectric which may be under electrical stress. It has been figured, for example, that if all the paper capacitors in the Bell System were unwound and laid out to form a single parallel plate capacitor, this unwieldy creation would cover a large section of Manhattan Island. And it needs only a minute puncture in one spot to ruin a whole unit.

As discussed in Chapter 1, in a capacitor under voltage the bound electric charges in the dielectric are under the strain of displacement from their normal positions. Just as there is a limit beyond which a spring cannot be safely stretched so there is a limit to the voltage that can be safely applied to a capacitor. The thicker the dielectric, the higher this voltage. Also, as for a spring, there is a considerable difference between the tension which a capacitor can stand for a few seconds and that which it can withstand continuously for months or years.

If we apply a voltage to a capacitor and increase the value rapidly, the dielectric will eventually rupture at a value which is characteristic of the type of dielectric and its thickness and which is sometimes termed the "ultimate dielectric strength." The working voltage which the capacitor can stand continuously is but a fraction of this ultimate dielectric strength and the value of this fraction varies considerably among different types, being as small as 1/10 in some cases. Intermediate between the safe working voltage and the ultimate dielectric strength voltage is what is known as the "flash" or "dielectric strength test" voltage. This is usually two or three times the

safe operating voltage, and is used in the factory as a test to insure that the capacitor is free of random mechanical defects and has been properly manufactured so far as such a test is capable of indicating.

It is important to recognize that neither this ultimate dielectric strength nor the factory flash test is of itself a reliable indicator of the maximum voltage which the capacitor can undergo continuously. Furthermore, transient voltages such as those which occur when electronic apparatus is started up are always a hazard if their magnitude appreciably exceeds the maximum safe operating voltage.

Under the influence of electrical potential chemical and physical processes and corona effects are set in motion which lead to deterioration and eventual breakdown of the dielectric. In general, the hotter the dielectric and the higher the voltage, the faster the wear. The rate of wear also depends on the nature of the dielectric and is much accelerated by the presence of water and other impurities which tend to take part in chemical activity. In electrolytic and impregnated-paper capacitors deterioration may proceed rapidly even at comparatively low potential gradients unless the most careful control is exercised as to the type and the purity of the materials and of the entire manufacturing process.

At present there remains much to be learned about capacitor life performance and the physical and chemical laws governing it. The war-time need for large quantities of durable capacitors greatly stimulated interest in probable life performance and in how to test for it and predict it. Now with the constant need to utilize the full capabilities of dielectrics and to explore new ones in order to meet the demands of the electronic art, the future is likely to witness much further development in the theory and practice of capacitor life-testing as a systematic art.

Of special interest is the life of impregnated paper dielectrics under direct voltage—for two reasons: First, paper capacitors are extensively used in electronic equipment; second, different types of paper capacitors have been found to exhibit

considerable variations in their life performance under the high potentials at high temperatures which so often prevail.

For some types, every 10° C rise in temperature produces a 50 per cent decrease in life; this means that a capacitor capable of operating continuously for the normally ample period of ten years at room temperature under a given voltage will last only a scant six months under the same voltage when it is at high temperatures. Not all paper capacitors are as temperature-sensitive as this. However, it points the precaution that, in selecting a paper capacitor for direct voltage use, it is vitally important to keep in mind the minimum length of life which will be required under the continuously applied operating voltage while the capacitor is at the maximum operating temperature. Also be sure that the manufacturer knows whether you expect his product to last six months or ten years.

In capacitor catalogs put out by the trade, rated working voltages commonly apply to the capacitor working at room temperatures (up to 40° C), and the safe working voltage applicable under higher temperature conditions may be considerably less than the value given. Consequently, to insure adequate life at high temperatures, we may need a capacitor of higher "voltage rating"—and therefore of considerably larger size—which is important from an apparatus assembly standpoint (see Fig. 16).

Suppose, for example, that a capacitor is to be subjected to 500 volts d-c. If it is also to work at room temperatures then a capacitor rated at 600 volts may well be capable of providing ample life. Suppose, however, that it later appears from our tests that for unforeseen reasons the temperature actually rises to 70° C and stays there for long periods. Then we may be compelled to substitute a capacitor of the next higher rating commercially available, usually 1000 volts, in order to insure the desired life at 500 volts, at 70° C. Unfortunately, this 1000-volt capacitor (if the capacitance is large) may be 3 or 4 times as large as the 600-volt unit previously chosen—indeed a distressing discovery to make after we have completed

the mechanical design of the apparatus chassis! So it pays us to find out early in the game whether the capacitor of our choice has enough dielectric to stand the service.

In general, the life of a paper capacitor under direct voltage decreases as the magnitudes of the voltage and of the ambient temperature increase. Stated in other terms, destructive processes proceed more rapidly as the level of the electrical energy and of the heat energy present in the di-

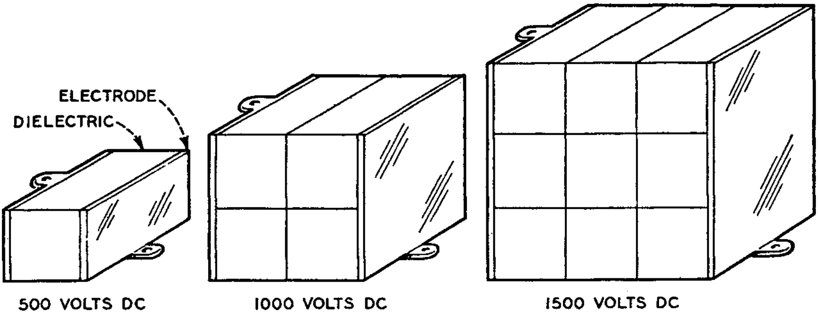


FIG. 16. Volume of dielectric increases approximately as square of voltage for constant potential-gradient and capacitance.

electric increase. In the quest to assure adequate direct-voltage life, the so-called fifth-power law has proved so valuable that it is here given some detailed consideration. It states that, at constant ambient temperature, the direct-voltage life is inversely proportional to the fifth power of the applied voltage.[1]

Suppose we subject to sustained direct voltage a group of capacitors which have passed a suitable dielectric strength test. There is an initial period during which no significant failures occur. At the end of this period, there occurs an inflection in the failure-distribution curve where significant failures start and thereafter continue to take place according to a definite pattern. This initial period which we shall denote as "*L*" represents the minimum life to be expected of the group under the specific applied voltage. Generally it is this minimum life, rather than the average or maximum, which is of primary in-

terest from the standpoint of insuring trouble-free capacitor operation.

Experiment has shown that L varies approximately as $1/E^n$ when E denotes the direct-current potential across the capacitor terminals. The value of n has been found experimentally to range from 4 to 6 for capacitor impregnants in general use at the present time, and on the basis of capacitance values up to 4 microfarads, ambient temperatures up to 85° C, test voltages up to 3000 volts, potential gradients up to approximately 1500 volts per mil of impregnated paper dielectric, and provided the internally generated heat due to direct currents is small.

It has been found to apply to liquid impregnants and also to waxes from room temperature up to near the melting point of the wax. There are indications that it does not apply where failure is apparently complicated by causes other than progressive deterioration of the dielectric attributable to externally applied heat and voltage; for example, with some wax-type impregnants which show a tendency to fail under direct-current potentials during temperature swings below room temperature or during the change from solid to liquid at the melting point of the wax.

This purely empirical formula for life versus voltage provides a useful working basis for determining safe operating voltages by means of accelerated life tests. Fig. 17 shows cumulative-failure distribution curves at different voltages plotted on the basis of $n = 5$. With reference to Fig. 17 suppose we wish to estimate the minimum life of a particular design of paper capacitor which will be required to operate under a direct voltage (E) at ambient temperatures reaching 90° C. Also, suppose that an adequate number of samples representing this capacitor show a minimum life of 10 days under a voltage of $2.5E$, or 30 days at $2.0E$, at a sustained temperature of 90° C. It follows from the fifth-power relationship that this capacitor could be expected to have a life in excess of 1000 days (more than 2½ years) when operated

at the expected operating voltage (E) with the temperature sustained continuously at 90° C. It is further to be noted that a service life considerably in excess of 1000 days could be expected of this capacitor where, as in most types of service, the capacitor would not be operated 24 hours per day or continuously at the maximum temperature while under voltage.

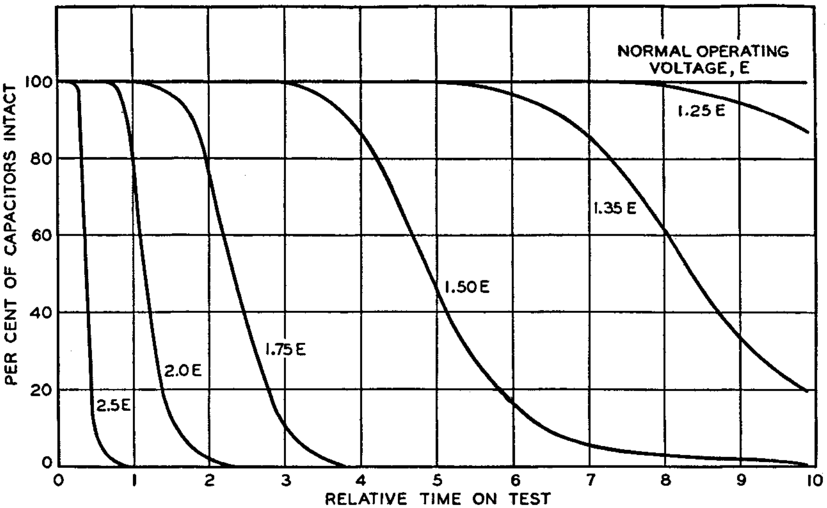


FIG. 17. Cumulative-failure distribution curve for paper capacitors showing effect of direct voltage at constant temperature.

Similar short-time accelerated tests can also be used to insure a 10- to 15-year life.

The length of life required is to be gauged in terms of the function of the equipment and of the service expected of it. In telephone repeaters or radio broadcast stations where a single capacitor failure can have serious consequences long life and reliability are paramount. In such equipment it is sound engineering to install capacitors capable of at least 15 years of life while the capacitors are continuously under voltage. In other equipments it may be expedient to sacrifice the assurance of long life to secure small size; for example, in radio sets which face rapid obsolescence or in portable test equip-

ment which is used only occasionally and in which a failure would not have serious consequences.

Experience shows that an accelerated life test on representative samples is the soundest basis for estimating the probability that capacitors will stand up in service. This is because new materials, new combinations of materials or new operating conditions are likely to engender destructive chemical or physical changes which are beyond the capabilities of present-day theory to predict. It is therefore most desirable that capacitors which involve radically new design, materials, or sources of supply for materials, or are required to meet service conditions not hitherto encountered should be rated only after life testing under accelerated voltages and in combination with temperature conditions at least as severe as those in prospect. The validity of any voltage rating must be evaluated in terms of the temperature at which the capacitor is to operate.

Rigorous life testing has paid rich dividends in the task of providing trouble-free capacitors for the Bell System. Prospective purchasers who demand to be shown life-test data or their equivalent on the capacitor they propose to use are best serving their own interests, at the risk, however, of becoming unpopular with salesmen.

Under direct voltage a capacitor remains steadily polarized and no current flows except for a small leakage drain which is usually negligible. So it is necessary simply for the dielectric to withstand the steady electrical stress.

Under alternating voltage a capacitor must also be able to withstand the maximum potential applied, but there is an additional factor which enters the picture. It is that, as the capacitor repeatedly polarizes and de-polarizes in unison with the alternating voltage, a current flows, generating heat.

Now a capacitor can develop just so much heat without the dielectric breaking down or literally burning up; how much depends on the power factor of the capacitor and its ability to conduct heat away from the dielectric; improving both factors is of prime concern in the design of a-c capacitors

required to handle large amounts of power. A capacitor's a-c capabilities are therefore limited by the current it can carry without becoming too hot. Now the magnitude of the current increases with rising frequency (for constant r.m.s. voltages). So the capacitor rating for a-c use must be limited not only as to maximum voltage stress but also as to maximum operating frequency.

For this reason capacitors intended for a-c operation commonly bear a frequency rating as well as a voltage rating. As users, we must bear in mind that a capacitor rated to work, let us say, at 60 cycles may not be safe to use at a higher frequency under the full-voltage rating applicable at 60 cycles.

To summarize, direct-voltage life is limited primarily by the magnitude of unidirectional electric pressure which the dielectric can withstand and alternating-current life, by the ability of the capacitor not only to withstand voltage but also to carry current. These are radically different conditions which make different demands on materials, on the types of impurities which can be tolerated and in methods of construction. For this reason, capacitors differ widely and sometimes unexpectedly in their relative performances under direct and alternating voltage. There are spectacular examples of capacitors which, although capable of excellent life performance under alternating voltage, rapidly develop destructive electrolytic-type reactions under direct voltage. It all adds up to a simple caution: Never draw conclusions as to probable life under direct voltage on the basis of the life exhibited under alternating voltage—or vice versa.

Summary of Factors Relating to Capacitor-Endurance under Voltage.

Capacitors under voltage may be subject to gradual deterioration leading eventually to breakdown, through their solid dielectrics and to a lesser extent through or over their other insulation. This wear stems primarily from the high voltage gradients (compared with those in insulation for most other uses) under which capacitor dielectrics are worked in

order to conserve space. It varies markedly for different dielectrics and capacitor designs and even among different manufacturing lots of a specific type, being extremely rapid in some instances and practically absent altogether in others. Because of this hazard, the suitability of a capacitor type must always be evaluated in terms of its probable endurance under the expected operating conditions.

The rate of wear increases with increasing temperature as well as with increasing voltage. Consequently a voltage rating is incomplete unless related to a specific operating temperature range, and especially to the maximum temperature.

Short-time dielectric strength or "flash" tests are not a reliable indicator of probable endurance under sustained voltage.

Repeated voltage pulses lasting only a few microseconds may puncture the dielectric if appreciably in excess of the rated voltage.

Properly designed and well-sealed capacitors do not deteriorate internally when not under voltage (except in the case of the electrolytic type, as covered on page 62). It is, therefore, economical to base life requirements on the actual time during which the unit will be under voltage rather than on the expected over-all service life of the equipment.

Usually a higher safety factor means a larger capacitor (Fig. 16). So the question of life should be taken up early in an apparatus chassis design to avoid the later necessity of redesign to accommodate a unit of larger size than originally contemplated in order to insure adequate life.

In direct voltage capacitors the sole consideration is ability to withstand sustained unidirectional electrical stress. No current flows other than the small residual leakage current.

Under alternating potential, there is an alternating current which generates heat and increases with rising frequency. The operating range is therefore restricted to an upper frequency limit as well as by a maximum voltage.

Life performance under direct voltage is not a reliable

indicator of probable performance under alternating voltage or vice versa.

A capacitor may seriously overheat when operated within its voltage rating but at above the rated frequency (page 34). There is the same hazard—particularly in high-frequency capacitors—if the unit is worked within its current rating but at below its minimum rated frequency (page 34). At high frequencies, operation above rated frequency may involve additional losses of damaging magnitude due to eddy current and other losses peculiar to high frequencies.

Under direct or alternating potential, flashover voltages between terminals (or between the plates of air capacitors) are greatly reduced at high altitudes.

Best single insurance of adequate life—in the present state of the art—is an accelerated life test on representative samples. Where reliable performance is a prime consideration, the manufacturer should be asked to furnish appropriate life test data.

Reference

[1] "Paper Capacitors under Direct Voltages," M. Brotherton, *Proc. I.R.E.,* Vol. 32, pp. 139–143, March, 1944.

CHAPTER 4

Which Capacitor Shall We Use?

What type of capacitor shall we use? The market offers for our consideration a wide variety of capacitor types each of which is usually named after its dielectric because of the dominant role played by the dielectric: Electrolytic, impregnated paper, mica, ceramics, plastics, air, certain gases and even a vacuum. There is no telling what new types tomorrow may bring. For simplicity this book has been limited to dielectrics in general use at the present time. Also no attempt has been made to depict the multitude of different available containers and methods of mounting which may be readily seen through reference to trade catalogs.

Always there is one thing to bear in mind. When we buy a capacitor we acquire a great deal more than a specific value of capacitance because a capacitor represents a specific combination of electrical and mechanical characteristics of which capacitance is but one. So even though we seek only one characteristic we must, nevertheless, accept the entire group. Each of the mass-produced commercial capacitor types has achieved its wide use because the characteristics it offers can be effectively utilized as a group in electrical apparatus. These major groups of characteristics provide a framework on which to examine our ideas and judgements and to calibrate them.

In choosing among these various types the capacitor user is not infrequently faced by a dilemma. He finds that in selecting a particular kind of dielectric because it offers some indispensable characteristic he is forced to make important sacrifices in other desirable but less important properties as to performance, space or cost. The best capacitor for our use is the one which offers the optimum combination of properties.

The group characteristics of the three types which have been the big runners—electrolytic, impregnated paper and

mica—are illustrated in Fig. 18. Broadly they span the gamut of electrical capacitor characteristics. Electrolytics offer large, cheap blocks of capacitance with comparatively poor

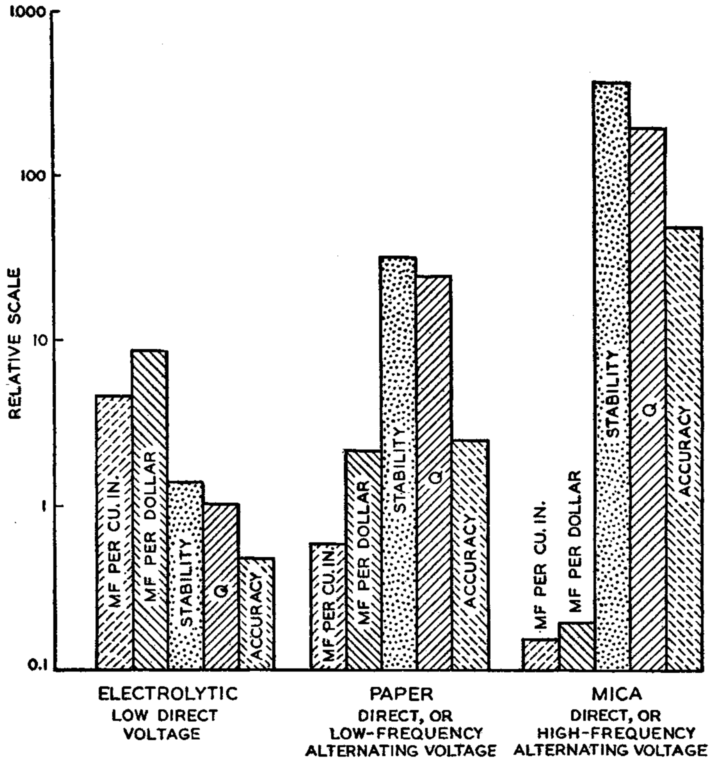


FIG. 18. Relative advantages of electrolytic, paper and mica capacitors. "Stability" is expressed as inverse of capacitance-temperature coefficient and "accuracy," as inverse of capacitance limits realizable without elaborate techniques.

electrical characteristics, whereas mica provides small capacitances with very good electrical characteristics. The middle ground is filled by the impregnated paper type which combines enough of the good characteristics of electrolytics and mica to make it suitable for more different uses in electric circuits than any other type. In addition, there are ceramic capacitors which provide special electrical characteristics or valuable combinations of electrical and mechanical characteristics not

realizable with other types. Air capacitors enter the picture to provide continuously variable small capacitances for tuning purposes. Dielectrics of polystyrene, Diaplex, cellulose acetate and glass also enter the picture. Despite some overlapping each type is normally employed to perform a fairly well-defined function.

As a broad guide, the common applications of the types in greatest demand and which you are most likely to use are summarized in Table 1. Subsequent chapters describe their nature, construction and characteristics with the object of showing what you may expect of them and, which is equally important, what you may not reasonably demand of them.

TABLE I. COMMON APPLICATIONS OF MAJOR CAPACITOR TYPES

Electrolytic	Large capacitance (8 mf or more). Capacitance limits and Q, not important. Small size per mf for large capacitances. Lowest cost per mf. D.C. operation only (not above 450 v). A.C. not above 120 v and only for short periods.
Impregnated paper	D.C. operation up to the highest voltages. Large a-c currents at low frequency only (less than 1000 cps). Medium accuracy (up to ±5%). Medium stability (0.02% per degree F). Capacitances (greater than 0.01 mf). Medium power factor (Q greater than 100 at 1 kc).
Mica	Capacitance (less than 0.05 mf). High initial accuracy (up to ±0.25%). Low capacitance drift (less than 0.1%). High stability with temperature. Low power factor over wide frequency range (Q greater than 2000).
Ceramics	Positive or negative capacitance-temperature coefficients of specified magnitude. Capacitances less than 2000 mmf. Low power factor over wide frequency range (Q greater than 1000). High stability with time.
Air	Continuously variable small capacitances (less than 1500 mmf).

CHAPTER 5

ELECTROLYTIC CAPACITORS

In the design of electronic apparatus, the need for economy in dollars and space cracks a mean whip. So where very large capacitances are required we look hopefully towards the electrolytic capacitor since this type provides more capacitance

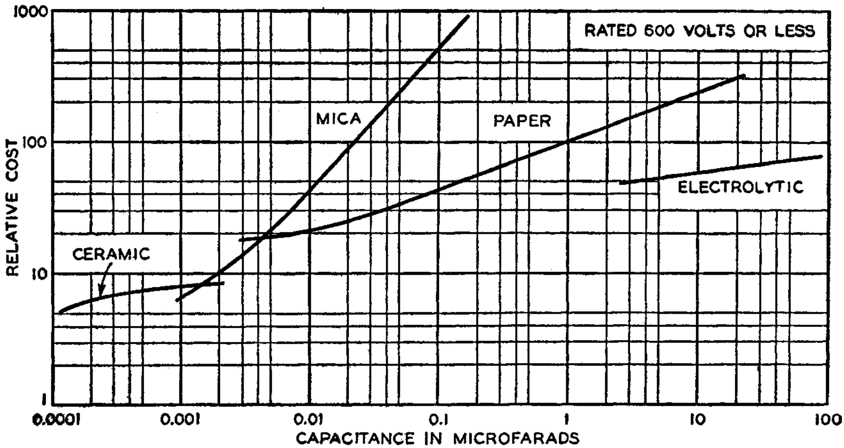


FIG. 19. Relative cost of electrolytic, paper, mica and ceramic capacitors.

in a given space and at a lower cost per microfarad than any other (Figs. 18 and 19). These capacitors (Fig. 20) are familiar items in home-radio sets where the provision of large filtering capacitances in very small space is a primary consideration. So far as the capabilities of the electrode-dielectric structure alone are concerned over 100 microfarads may be contained in 1 cubic inch for very low voltage operation; 25 microfarads, at the higher voltages. It is even possible to accommodate over 1000 microfarads per cubic inch where the

voltage to be applied is less than 3 volts. However, practical electrolytic capacitors are much larger than these space figures imply on account of the relatively enormous space needed to mount and seal the unit and provide terminal connections. Electrolytic capacitors are not normally supplied in units of less than 8 mf.

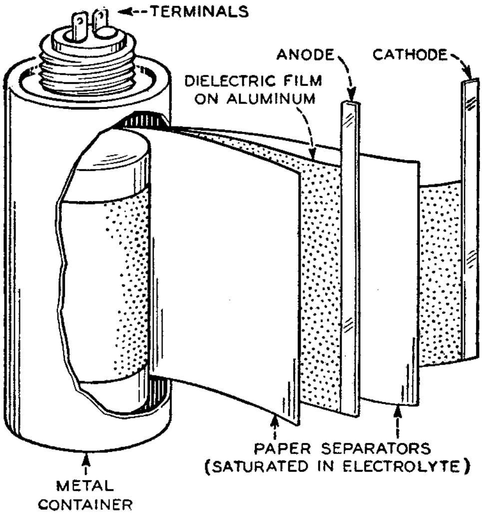


FIG. 20. Electrolytic capacitor.

The attractive space economy of electrolytic capacitors derives from the extreme thinness of the dielectric which is an insulating film of oxide previously built up by an electrolytic process on one of the electrodes, known as the anode (capacitance per cubic inch is inversely proportional to the square of the thickness of the dielectric). The thickness of this insulating oxide film is but a few millionths of an inch and the working voltage gradient is of the order of 10 million volts per inch.[2] Etching the anode increases the effective area so as to increase the capacitance as much as 700 per cent.

Unlike other commercial dielectrics, this electrolytic film is a one-way street for electric current, like a rectifier. With the voltage applied in one direction, the film has a high re-

sistance to the flow of current and behaves like a dielectric. With the voltage reversed the film behaves like a relatively low resistance and, if the voltage is high enough, it passes large currents, heats up and soon breaks down. Because of this unidirectional property, the film is suitable only for direct voltage in a single direction and the anode terminal is usually marked "positive" to indicate in which direction the voltage shall be applied.

In what is probably their most extensive use, namely as plate filter capacitors, they are subject to direct voltages with a small superimposed a-c ripple so that the total voltage never reverses in polarity. However, chiefly because of the inherent limitations in the thickness to which insulating electrolytic films can be used in the presence of suitable electrolytes, the safe operating voltage is limited in commercial capacitors to about 450 volts d-c.

Electrolytic capacitors are also supplied commercially for a-c operation, and this type consists virtually of two capacitors with their anodes connected together so that the two capacitors operate in series but in opposite directions. One capacitor absorbs the applied voltage on one half of the a-c cycle and the other capacitor comes into play during the succeeding half-cycle when the voltage reverses. Such capacitors are used extensively on low a-c voltages; for example, as motor-starting capacitors when the full voltage is of short duration. Where the voltage is very low, they can be used continuously; for example, to filter audio frequencies in radio sets. In general, they are severely limited on a-c with respect to voltage because of the high power factor.

The electrolytic capacitor is not suitable for precision circuits. The initial capacitance value may be as much as 100 per cent greater than the nominal. Added to this are the large variations in capacitance and resistance, and consequently in over-all impedance, especially at low temperatures, shown on Fig. 21. Aging may cause a progressive capacitance decrease eventually totaling 20 per cent or more. For these reasons, these capacitors are generally limited to filter and by-

pass uses where large variations in characteristics can be tolerated. By the same token, they are not suitable for use in conjunction with coils in tuned circuits or in other applications requiring stability of characteristics and limited a-c loss.

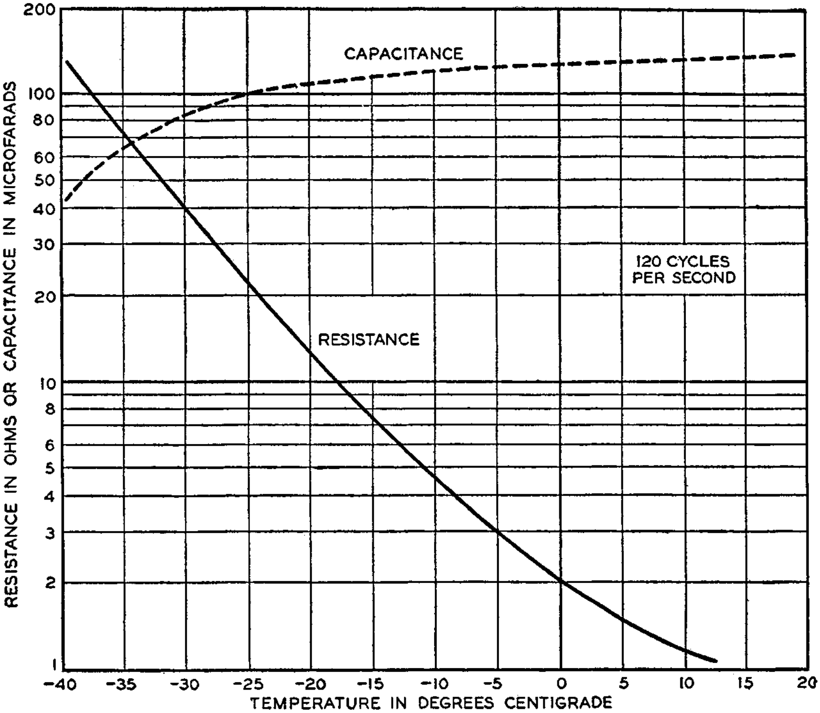


FIG. 21. Capacitance and effective resistance versus temperature for electrolytic capacitor.

Unlike the dielectric in other capacitor types, the film is subject to deterioration in spots where foil impurities are present, when the capacitor is left idle for long periods. When full voltage is again applied, leakage currents at these spots may be large enough to destroy the weakened film before it can be repaired by the electrolytic action. Consequently, it is inadvisable initially to apply full-rated voltage to a capacitor which has been at zero voltage during a period of many months. Also, since heat accelerates deterioration of the

film, this precaution becomes particularly important when the capacitor has been stored in the tropics or other hot places. Electrolytic capacitors give most satisfactory service under continuous operating conditions.

The dielectric strength and life expectancy of the electrolytic film depend critically on the purity of the original materials as well as contamination during manufacture. There is very little published information on the life performance of these capacitors. However, experience shows that standard commercial capacitors if properly made will operate on full-rated voltage at temperatures up to 150° F for satisfactory periods in many types of equipment. Up to ratings of 400 volt d-c, they can be made to withstand still higher temperatures by special processing and suitable rating.

Electrolytic capacitors are advantageously used in telephone offices in blocks of 1000 microfarads to by-pass the "noise" from battery-charging machines which would otherwise disturb the telephone system.

To summarize, electrolytic capacitors are most advantageous where very large capacitances are required to work as filtering or by-pass capacitors under direct voltages. Their usefulness in other connections will undoubtedly grow as means are developed to improve their stability. For more detailed information on these capacitors the reader may refer to books by Coursey[1] and McKnight Deeley.[2]

Commercial electrolytic capacitors range in size from a finger to a quart paint can and are generally housed in metallic containers. For less critical uses, the smaller sizes are mounted in cardboard cases.

Principal Uses of Electrolytic Capacitors.

1. Filtering in d-c circuits, especially where big blocks of capacitance are needed, at low cost, and in small space.
2. Motor starting.
3. By-passing audio-frequency currents where the unit is under direct voltage and the alternating voltage is never large enough to reverse the potential.

References

[1] *Electrolytic Condensers,* by Phillip R. Coursey, Chapman and Hall, 2nd ed., London, 1939.

[2] *Electrolytic Capacitors,* by Paul McKnight Deeley, Cornell Dubilier Corporation, South Plainfield, N. J., 1938.

CHAPTER 6

Impregnated Paper Capacitors

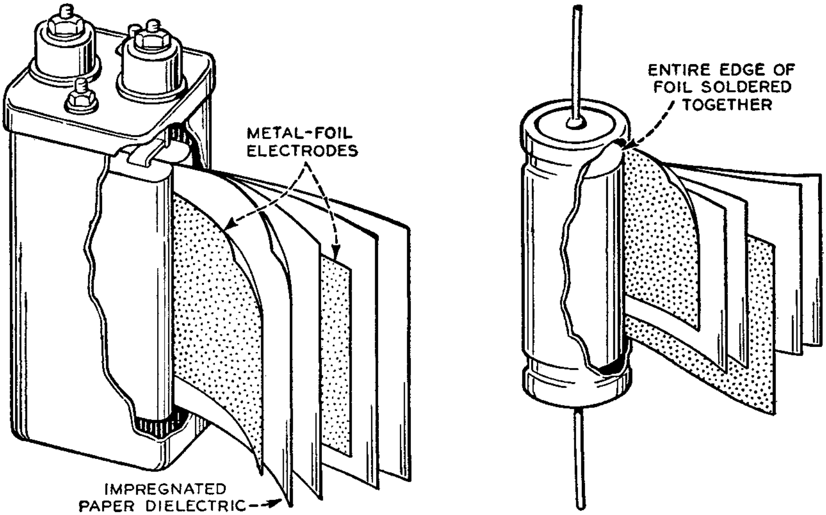
This brings us to the most versatile of all capacitors, the impregnated paper type. Your electronic equipment, whatever it may be, probably includes at least one. We use this type where electrolytics are inadequate electrically and where the low loss and high stability of dielectrics such as mica are unnecessary; in other words, for by-pass and rough filtering purposes. Next to the electrolytic capacitor, the paper capacitor provides low-voltage capacitances down to about 0.01 microfarads in the smallest space at the lowest cost (see Figs. 18 and 19). It is amenable to great flexibility of design and has more diversified uses than any other type, extending from the massive high-voltage power capacitors to pigmy styles smaller than a cigarette. Paper capacitors may be designed to work on alternating as well as direct voltages up to the highest values (they have been built for 200,000 volts or more), and they can be built to carry large a-c current at low frequencies.

The ratio of volume per microfarad is very much larger for paper capacitors than for electrolytic capacitors. Even low-voltage paper capacitors occupy five to ten times the volume required for electrolytic types of equal capacitance. On the other hand, a low-voltage 1 mf paper capacitor may be only about one fourth the size of a corresponding up-to-date mica capacitor of equal capacitance and working voltage.

Convenient to make and handle, the basic unit which supplies the capacitance is usually made by winding up two metal foils, separated by two or more sheets of paper (see Fig. 22). Another advantage which may not be immediately apparent is that the wound unit has twice the capacitance it would have

if the roll were unwound and laid out flat so as to form a parallel plate capacitor.

These basic units are capable of being wound over a wide range of sizes and paper dielectric thicknesses and combined in series or parallel within a capacitor to supply a large range of capacitance values and working voltages. Because of their



(a) LAID-IN TERMINAL UNIT (APPROX. HALF SIZE)

(b) EXTENDED FOIL UNIT (APPROX. FULL SIZE)

FIG. 22. Paper capacitors in hermetically sealed housings.

mechanical advantages, useful electrical characteristics and cheapness, impregnated paper dielectrics have been the subject of more study than any other dielectric in connection with capacitors, as well as for power cables, with the object of attaining better characteristics and longer life.

The unit is impregnated, after drying, with a wax, oil or a synthetic compound. Mechanical flexibility and ease of impregnation give paper an outstanding advantage over other dielectrics which have superior inherent dielectric properties but which are inflexible mechanically or are relatively difficult to impregnate. Paper can be readily impregnated with resins,

waxes, oils or synthetic compounds to give a wide variety of characteristics. In these characteristics, paper capacitors have important limitations due chiefly to the limitations inherent in the paper or impregnant itself.

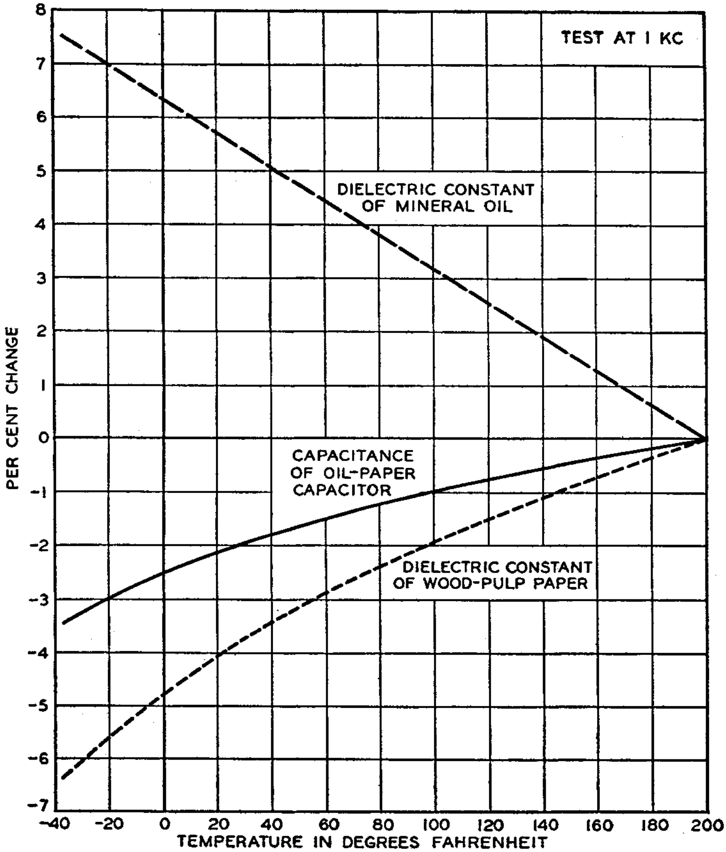


FIG. 23. Capacitance-temperature stability of paper capacitor depends on relative contributions from oil and paper.

Paper, impregnant and electrode material—all contribute to the characteristics and performance of the capacitor. In a two-sheet Halowax capacitor about 50 per cent of the dielectric constant is contributed by the paper and 50 per cent by the Halowax. Turning to Fig. 23, covering mineral oil-

impregnated paper, we note that the dielectric constant of paper alone increases as the temperature rises; that of mineral oil alone decreases. When the paper and mineral oil are

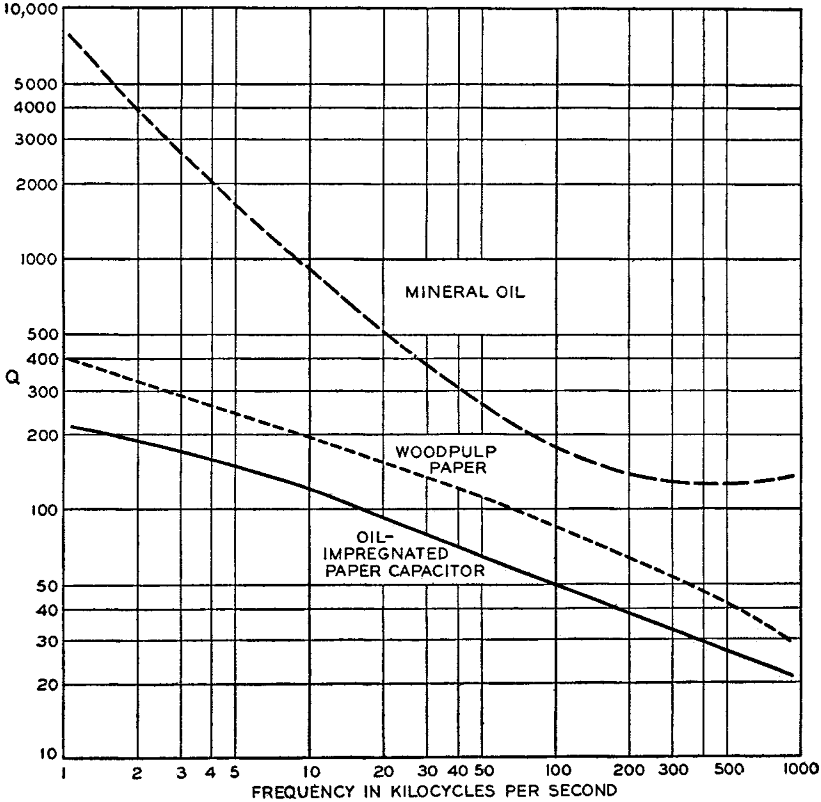


FIG. 24. Q versus frequency for mineral-oil paper capacitor. Shows limitation imposed by relatively poor Q of paper.

combined to form impregnated paper, consisting approximately of 40 per cent oil and 60 per cent cellulose, these opposed effects are combined with the result shown. Note the dominating influence of the paper due to its higher dielectric constant. Fig. 24 shows the relative influences of the paper and the impregnant on the Q of a mineral-oil impregnated capacitor. It is evident from Figs. 23 and 24 that the properties of the paper itself severely limit the capacitance stability

and the excellence of the Q realizable in impregnated paper capacitors.

Within the limitations imposed by the paper itself, commercial capacitors are manufactured to offer a broad range of characteristics through the use of different impregnants. The capacitance-temperature characteristics, a matter of frequent interest, are illustrated for some leading commercial varieties in Fig. 25.

Both wax and liquid impregnants are used. Waxes have been quite successful under moderate direct voltages and at room temperature; for example, in the paper capacitors of the Bell System. Liquids are superior under the higher direct and a-c voltages and at very high or low temperatures. Unlike waxes which melt at high temperatures, abruptly changing in volume by 10 per cent or more to distort the dielectric and which at low temperatures may severely contract or even crack to open up voids in the dielectric, liquids which remain fluid over the operating range merely undergo a gradual change in volume and viscosity as the temperature swings. The current trend is toward the use of liquid impregnants to meet the growing severity of temperature conditions in electronic equipment.

In no other type of capacitor except electrolytic are high standards of manufacture more essential to reliable performance than in paper capacitors. The impregnated paper dielectric must be free of air and of water and other impurities likely to engage in chemical action. Even in the most carefully made capacitors, freedom from these unwanted elements is only approximated. This is because capacitor paper, usually made of wood pulp, contains residues of salts or of acidic or alkaline substances even after the most careful washing during manufacture. Impregnants may also contain chemically active impurities or may deteriorate under the combined influence of heat, voltage and the catalytic effect of the metallic electrodes to form chemically active substances. With some types of impregnants the nature of the foil profoundly

influences durability under voltage. Aluminum which can be made to a high degree of purity is usually the best performer.

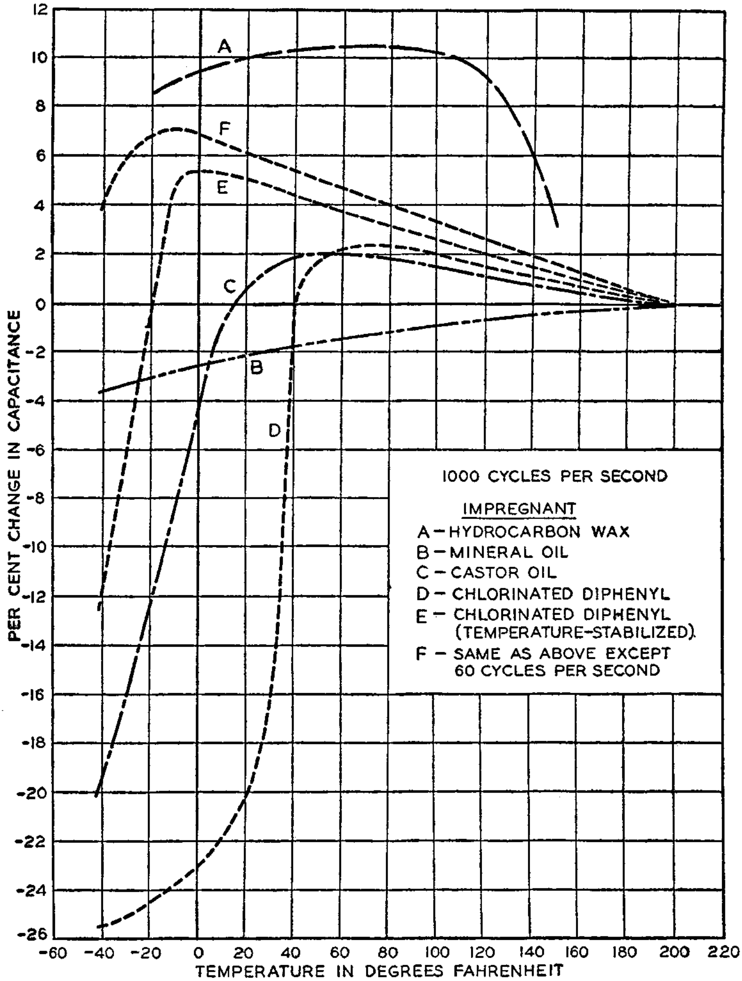


FIG. 25. Capacitance versus temperature for paper capacitors using commercial impregnants.

Impurities contribute to the dielectric loss and to the d-c leakage current and stimulate further deterioration of the dielectric. Under alternating voltage they produce heat in the dielectric. However, the most marked effects are observed

under the steady electric pressure of direct voltage, where electrolysis sets in. Tiny spots of impurity which would be innocuous under low voltage and low temperatures may become seething cauldrons of chemical activity at high voltage combined with high temperatures.

Chemical activity is accelerated in the presence of water, and it is therefore a primary objective of sound capacitor manufacture not only to employ paper and impregnants of the highest purity commercially obtainable but also to reduce the amount of water in the dielectric to the absolute minimum by careful drying. By no means least is the final task of providing a seal which will positively prevent the entry of moisture after the capacitor has been assembled and placed in service.

At first sight, it might appear to be a simple matter to dry a material so porous as capacitor tissue. However, paper being highly hygroscopic tenaciously holds water, retaining under average atmospheric conditions about 5 to 6 per cent of water by volume; the water in a pound of paper would about fill an egg cup. Much of this water is relatively loosely held in and around the cellulose fibres. Some of it is firmly anchored to the paper by the powerful attractive forces which exist between the water and cellulose molecules and is therefore difficult to remove.

In practice, drying is effectively done by heating the paper to high temperatures in a vacuum to a point where the vapor pressure is sufficient to drive the water off. In very large capacitors, involving large, compactly wound paper units, several days of heating and evacuation may be required to conduct enough heat energy to the center of the units to establish the necessary vaporizing pressure. How to minimize this lively medium for ionic conduction and chemical action is a cardinal problem of the capacitor art. So important is it, that the Western Electric Company dries wound paper units to a moisture content of less than 0.1 per cent by weight of paper, checking the process by a method in which residual water is extracted from sample units and weighed.

Even when thoroughly impregnated, paper is capable of absorbing dangerous quantities of water if left exposed to the atmosphere, depending on the prevailing humidity and the water-resistant properties of the wax, oil or other impregnant. Consequently, the safest manufacturing practice is to dry and impregnate the units after assembly in a final housing so designed that it can be hermetically sealed on completion of drying and impregnation. Thereafter, that seal should remain sufficiently moisture-tight despite every degree of heat, cold and mechanical abuse forthcoming. That impregnated cardboard seal which may be adequate for capacitors under reasonably dry atmospheric conditions is likely to prove sadly wanting in the tropics.

Why such meticulous care must be exercised in excluding moisture and other impurities from the dielectric is better appreciated if we consider the enormous electric stress under which impregnated paper is commonly operated in capacitors in electronic equipment.

Typical is an ordinary 1-mf mineral oil-impregnated paper capacitor rated to work under 2000 volts d-c. The thickness of paper separating the electrodes in commercial capacitors of this voltage rating is about 2 mils. This means that the dielectric works under a potential gradient of 1000 volts per mil which is equivalent to 1,000,000 volts per inch. Now if we were to unwind the unit so as to form a parallel plate capacitor, it would cover an area about equal to that of four bridge tables. So we have the phenomenon of an area of paper insulation about 2 mils thick and sufficient in area to accommodate four bridge games working under a gradient of 1,000,000 volts per inch. In addition, we must not forget that every single spot in this area must be able to withstand this voltage since failure at even one microscopic spot would short-circuit the entire capacitor.

Compare the familiar electric lamp-cord which connects the bridge lamp to the wall socket and works under about 170 volts peak a-c between its conductors. Even with this low

voltage, there is the hazard of a flash-over when the rubber becomes old and damp. Yet if the rubber insulation of electric lamp cord worked under the same gradient as the impregnated paper dielectric in our 1-mf capacitor, it would be working under 120,000 volts between conductors. Little imagination is needed to appreciate how long the cord would last under a voltage gradient of this magnitude. Yet paper capacitors can be built to stand up many years under potential gradients of this magnitude even when working continuously in apparatus at the temperature of a hot cup of coffee. Those who are tempted to belittle the capacitor art are respectfully invited to ponder this phenomenon.

We may well ask: Why not design the paper capacitor to work under the same lenient voltage gradient as the lamp cord? The answer is that if we were to do this, our 1-mf, 2000-volt d-c capacitor would be larger than a suitcase, much larger indeed than the electronic apparatus units of which it commonly forms but a single component.

For many years mineral oils and waxes were the standard impregnating materials in high-voltage paper capacitors. But the capacitor specialist is relentlessly pursued by the demand for more capacitance in less space, so he is constantly on the lookout for usable materials of higher dielectric constant. More and more chemistry is meeting this need by building new compounds which through special molecular structures are capable of more polarization. Too often, however, the very properties which produce more polarization may also facilitate destructive ionization and a proneness to failure not found in mineral oils and waxes under comparable conditions of heat and electric stress.

There is probably no better example of the unknowns which threaten the capacitor engineer—and indirectly the user—than the unforeseen performance limitations of paper capacitors impregnated with chlorinated naphthalene and chlorinated compounds. One of these, chlorinated diphenyl (Aroclor), is extensively used in capacitors for power correc-

tion and for large-capacitance filtering in electronic circuits. Its high dielectric constant permits attractive space economy not attainable with mineral oils and waxes; it is an outstanding performer on 60-cycle voltages up to high temperatures; non-flammable and resistant to heat and oxygen, it can be made and subsequently maintained under factory conditions to a high degree of purity.

Their small size could be used to good advantage in the Bell System. So exploratory life tests were undertaken. They disclosed that these capacitors failed too rapidly under the twin pounding of heat and high direct voltage for use in the telephone service where a single failure could put an entire transcontinental circuit out of commission. Yet, these selfsame capacitors stood up a very long while under cool conditions.

Here, indeed, was a puzzle. Why should a material so highly stable as gauged by accepted chemical and physical checks, break down readily under conditions of high direct voltage and high temperature which would not destroy the inherently less stable mineral oil? Besides, this deterioration occurred in spite of the utmost care to preclude electrochemical impurities in the paper, foil and impregnant of which the units were composed.

We now know that chlorinated diphenyl tends to break down chemically of its own accord under direct voltage and heat in the presence of the catalyzing effect of the metal electrodes of a capacitor.[1] Then, under the driving one-way electric field the decomposition products engage in electrolysis destroying the dielectric in discolored spots which can be plainly seen if the capacitor is dismantled and examined even long before total breakdown has occurred.

First step towards the solution was the unexpected discovery that paper made from trees stood up far longer than the purer linen-base papers. Some factor in the wood pulp slowed up the destructive electrolytic action.

We may note in passing that this disclosure of a hidden

element in the paper which inhibited chemical action vividly illustrates the hazards faced by the synthetic chemist when he essays to simulate in the laboratory natural materials which may have acquired many unrevealed factors during the long and intricate processes of evolution and growth. Despite the numerous limitations of paper, we have yet to produce a synthetic which can equal it in overall efficiency in impregnated paper capacitors.

Guided by this "paper" clue the chemists set out to find a chemical agent which would have the same beneficial effect as the unknown in the wood. They found it in "anthraquinone," a compound in common use in the dye industry.[2] Dissolved in the chlorinated diphenyl, as little as ½ per cent of this yellow powder helped the capacitors to stand up for many months under accelerated life-test conditions instead of the few days previously attainable.

Then, they went a step beyond and found out that the life could be further improved by breaking a long-cherished rule in the drying of paper. They pre-baked it for many hours while it was exposed to the oxidizing effect of air at high temperatures. Instead of impairing the paper, this pre-baking rendered it more resistant to chemical action. This, incidentally, is another example of the unknowns in natural materials.

The joint effect of these two factors—anthraquinone and pre-baking—was to improve the direct-voltage life of chlorinated diphenyl capacitors over a hundred-fold at 90° C (see Fig. 26). Practically, it means that these space-economizing capacitors can now be used with safety in communication circuits and radio equipment under conditions of heat and voltage which quickly destroy them in the absence of these stabilizing treatments.

For capacitor engineers and users alike, there remains a single moral. Paper, impregnant, foil—every element that enters into a capacitor—each may be as good as can be made judged on its own merits. Yet put together they may produce a poor capacitor. So, theoretical reasoning as to probable

performance can never be conclusive. The best guarantee of good performance is a life test which truly reflects the expected conditions of operation. In any capacitor, it is the only sure way to trap "unknowns."

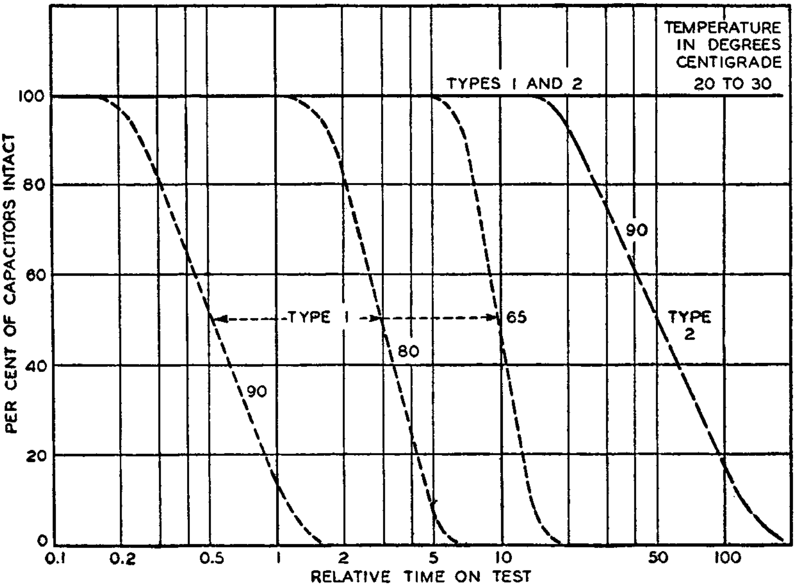


FIG. 26. Cumulative failure-distribution curves for paper capacitors showing effect of temperature at constant direct-voltage. Type 1. Pure chlorinated diphenyl impregnant. Type 2. Chlorinated diphenyl plus anthraquinone inhibitor.

Summary.

Impregnated paper capacitors are the most extensively used of all types because of their economy in size and cost and their flexibility of design. In larger capacitances, they offer the largest ratio of capacitance to size and cost with the exception of the electrolytic (Fig. 18). They can be built to work at the highest direct voltages and, on a-c at low frequencies, to carry large currents. At higher frequencies, they are severely limited by losses in the paper. In audio-frequency circuits of moderate precision they provide tolerable losses and adequate stability for many uses.

Because of the variables and impurities that can enter into the paper, impregnant and foil coupled with the high electrical stresses (volts per inch) under which the dielectric is customarily worked, meticulous care is needed in both design and manufacture for best service. Because of the affinity of water for paper and its strong activating effect on electrolizable impurities, hermetic sealing is mandatory for best service, particularly in moist atmospheres.

The length of life under direct voltage is inversely proportional to the fifth power of the voltage for constant temperature (within the limitations given on page 50). The effect of temperature is less well established but the assumption that the length of life is halved for each 10° C rise in temperature is found to provide a conservative basis for estimating purposes.

Paper capacitors on the market range in size from postage stamps or match sticks to suit cases. For best service the larger capacitances are protected by hermetically-sealed rectangular or tubular metal casings. High-voltage, low capacitance types are also housed in glass or ceramic tubes which afford long flash-over paths between terminals and ready insulation from ground. For less critical types of service, the smaller capacitances are housed in cardboard tubes or boxes.

Principal Uses of Paper Capacitors.

1. Primary filtering and by-passing.
2. Power factor correction and phase shifting at power and audio frequencies; generally, applications involving large currents or high voltages at low frequencies.
3. Filters and networks of moderate precision and loss requirements at audio frequencies.
4. Contact protection in relays; they are extensively so used in the Bell System.

References

[1] "Paper Dielectrics Containing Chlorinated Impregnants, D. A. McLean, L. Egerton, G. T. Kohman, and M. Brotherton, *Ind. and Eng. Chem.,* Vol. 34, pp. 101–109, Jan., 1942.

[2] "Paper Capacitors Containing Chlorinated Impregnants. Stabilization by Anthraquinone," D. A. McLean and L. Egerton, *Ind. and Eng. Chem.,* Vol. 37, Jan., 1945.

CHAPTER 7

Mica, Ceramic, and Air Capacitors

Mica Capacitors

The virtues of mica are very high electrical stability and very low a-c loss in which respects it is rivaled by few other materials. Its performance as compared with that of impregnated paper is brought out in Figs. 28, 29 and 30. A further advantage of mica capacitors is their adaptability to accurate, initial capacitance adjustment.

Mica for capacitors consists of a refractory mineral called muscovite; it occurs in nature in laminated form and can be separated into thin sheets. Nature has endowed mica with physical and electrical characteristics that make it an excellent dielectric material from a purely electrical standpoint. It is non-porous and relatively non-hygroscopic. The better grades of mica used for capacitors are substantially free of electrolytes, conducting particles and vegetable inclusions.

Associated with this chemical inertness are high stability of capacitance and power factor with respect to temperature and time and an ability to withstand electric stress even at very high ambient temperatures. Because it does not readily absorb moisture, it can be operated without dielectric failure in the presence of amounts of moisture which would rapidly prove fatal to paper capacitors. However, in order fully to realize the advantages of high capacitance stability and low losses it must also be protected from atmosphere moisture.

Essentially the unit of a mica capacitor consists of flat metal electrodes separated by a sheet of mica. Such units are connected in parallel to provide the larger capacitances, and their capacitances may be connected in series for the higher voltages. In small size, high-precision types it is advanta-

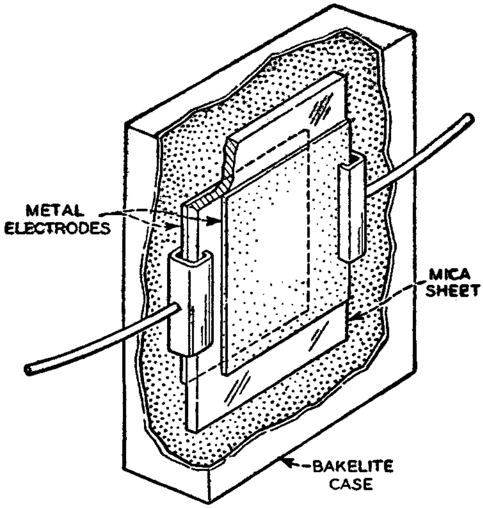


FIG. 27. Molded mica capacitor (enlarged).

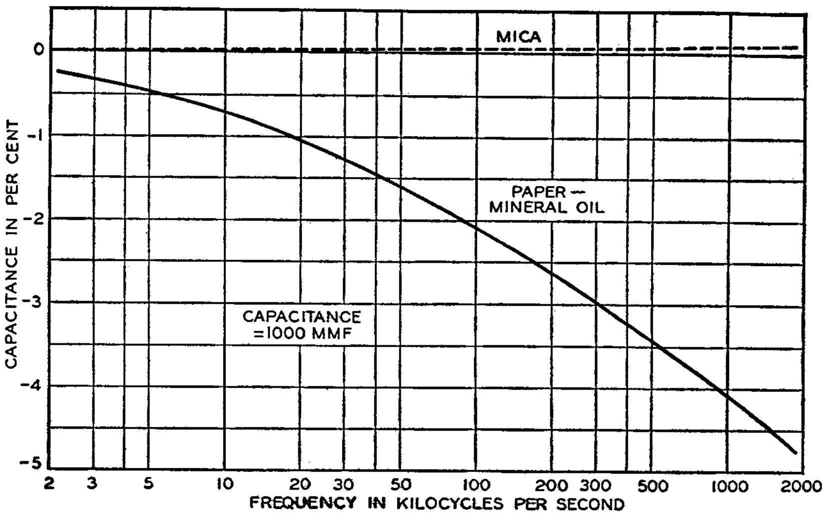


FIG. 28. Capacitance versus frequency for silvered mica and mineral-oil paper capacitors.

geous to employ electrodes made by bonding a deposit of silver directly on the surface of the mica ("silvered mica" construction). Fig. 27 shows the popular molded type in which the mica unit is molded into a protective housing.

Although mica capacitors have a good record as regards

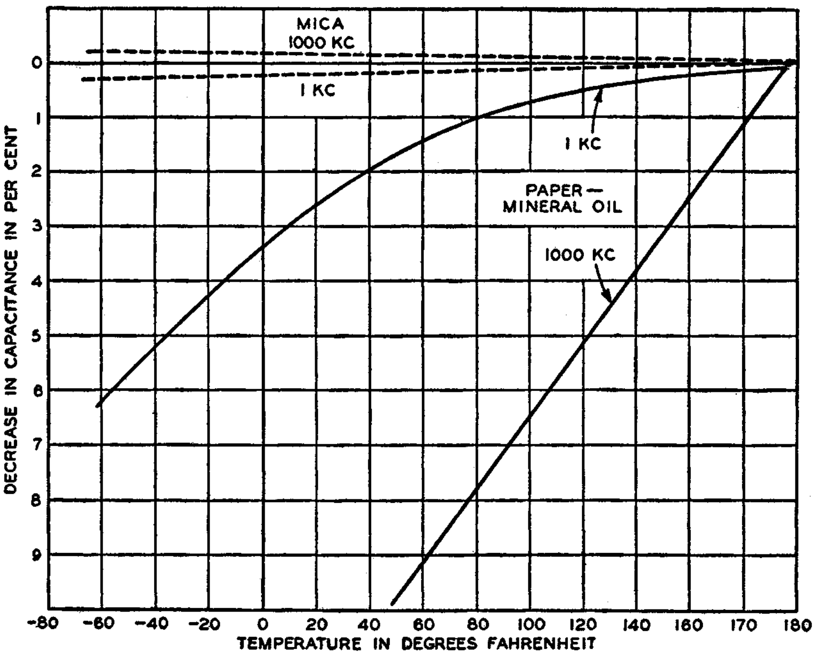


FIG. 29. Capacitance versus temperature for silvered mica and mineral-oil paper capacitors.

electrical endurance and stability, they are nevertheless also occasionally subject to defects in manufacture or to unknowns in a particular lot of the raw material. The thin sheets may be inadvertently cracked, delaminated or contaminated in handling during fabrication of the capacitors so that flash-over occurs sooner or later either through the sheets or around the edges. So here as with other types, sample life testing is needed to provide a criterion of probable endurance.

From a space per microfarad standpoint, in large capacitances a mica capacitor is much larger than a comparable paper

or electrolytic type (Fig. 18). A low-voltage mica capacitor of one microfarad occupies 3 to 4 times the volume of a corresponding design in paper and 30 times that of an electrolytic type on a comparable low-voltage rating basis. As compared with impregnated paper, mica has the important mechanical

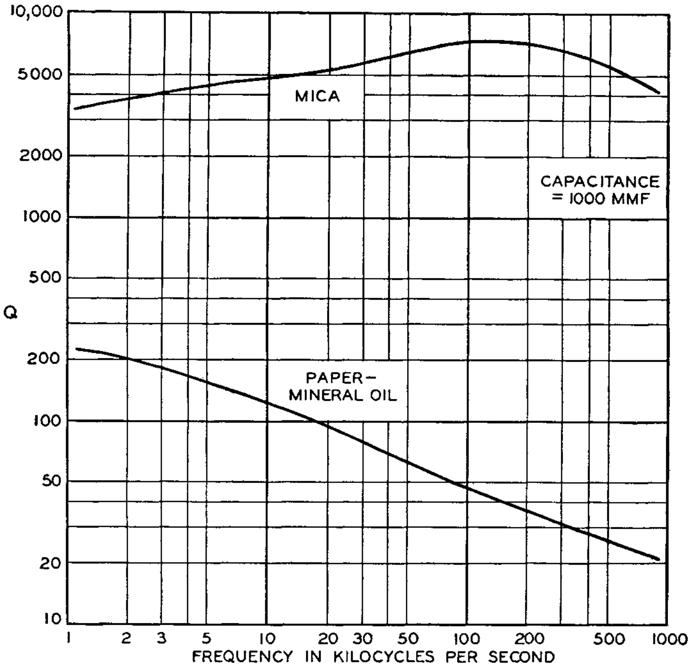


FIG. 30. *Q* versus frequency for silvered mica and mineral oil paper capacitors.

disadvantages that it cannot be split beyond certain minimum thicknesses and, being too inflexible to roll, must be used in flat sheets. Fortunately, the larger size per microfarad of mica in large capacitances is not a serious disadvantage in practice because the excellent characteristics which mica has to offer are usually required in combination with low capacitance values (less than 0.05 mf). In very low capacitances, whether in mica or paper, the smallness is often limited, not by the size of the mica or paper unit which provides the capaci-

tance, but by the casing and mounting which for mechanical reasons cannot be reduced below certain minimum dimensions. For these low capacitances, the mica approximates paper on a cost and size basis (Fig. 19) : it is capable of providing higher adjustment accuracy and also is often favored from the standpoint of the ease of manufacture. Consequently, for certain low-capacitance ranges, mica capacitors may prove more economical although an impregnated paper type would be adequate from an electrical standpoint.

Mica capacitors are used where it is essential to maintain an impedance to close limits with respect to temperature, frequency and aging, e.g., in tuning circuits which control frequency, reactance and phase or in measuring equipment such as capacitance bridges. They are also able to provide low-impedance paths to currents at high frequencies where the reactive component of the impedance is so small that the effective value of the impedance is controlled by the resistance component. At high frequencies mica dielectric capacitors provide low a-c losses far beyond the abilities of paper capacitors. Because of these low losses mica capacitors are used to handle high-frequency currents which would quickly burn up paper capacitors. The value of the voltage-current-frequency combination that a mica capacitor can carry is more often limited by corona or other losses which are extraneous to the mica dielectric.

Mica capacitors are supplied in metal, molded and ceramic casings; some, for restricted applications, have no casing at all. Molded and ceramic housings conveniently afford insulation from ground and from adjacent apparatus and provide long flash-over paths between terminals. There are also diminutive types affording very low capacitance which may be varied for circuit-trimming purposes.

Principal Uses of Mica Capacitors.

1. For high-frequency filtering and by-passing.
2. In filters and networks, working at well above audio frequencies.

3. For fixed tuning at high frequencies especially where high voltages and currents are involved.
4. As capacitance standards.
5. As trimmers for adjusting circuits.

Air Capacitors

Unlike capacitors having solid or liquid dielectrics the usefulness of air capacitors derives from the inherent ease with which their capacitance can be continuously varied in value by moving the plate electrodes (Fig. 31). We use them

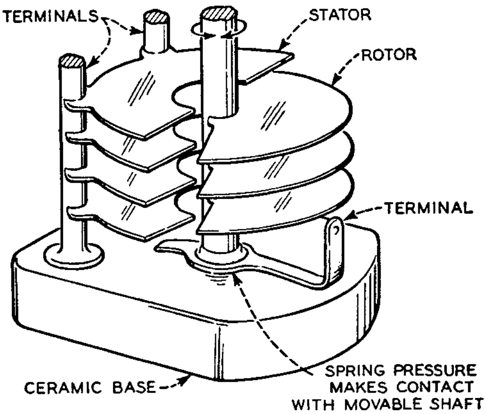


Fig. 31. Air capacitor.

to supply a smoothly variable capacitance value ranging from a few micromicrofarads to 1500 mmf. Connected in parallel with fixed capacitors, they provide means of adjusting the total capacitance value and, in conjunction with inductance coils, they are used to tune circuits and generally to control impedance and phase.

One set of plates is stationary while the other set is attached to a shaft which can be rotated so as to vary the effective electrical area. Various useful relationships between the capacitance value and the angular position of the shaft may be secured by properly designing the shape of the plates. In one type the capacitance is made to vary directly as the

angle of rotation. Where the capacitor is used to resonate with a fixed inductance the angle of rotation can be made proportional either to the wave-length or to the resonance frequency.

Of all capacitors the air type occupies the most space per microfarad. Much of this space is taken up by the mounting and the mechanism required to rotate the plate electrodes but it is also the result of the relatively low dielectric strength and dielectric constant of the air dielectric. In capacitance-temperature stability, they equal mica and, in addition, are subject to less a-c loss than mica. They are advantageous in applications requiring low-loss, high-stability capacitances of very small value. Relative to other types, the variable air capacitor provides the highest attainable accuracy of adjustment, the accuracy being limited chiefly by the precision of the drive mechanism.

Unlike capacitors having material dielectrics, the air capacitors depend for their excellence mainly on the material, dimensions and arrangement of the electrodes and on their supporting insulation. At high altitudes consideration must also be given to the reduced dielectric strength of air incident to the lowered pressure. All the a-c loss is in the plates and supporting insulators. Also the capacitance, once adjusted, must not drift or wobble even in apparatus under severe vibration. Therefore, with respect to a-c loss, stability and accuracy of adjustment, the good performance of an air capacitor depends vitally on its mechanical design, especially where the capacitor will be exposed to mechanical vibration or repeated rotation of the movable plates. The individual members of each group of plates must remain solidly connected together; a simple way to accomplish this is by soldering.

In some circuits, the movable plates are automatically maintained in almost continuous motion as the circuits respond to variations in incoming signals. Here the ability of the shaft bearings to withstand wear becomes a prime consideration.

Always to be watched is the possibility of poor contact de-

veloping in the moving contact connection to the movable plates, especially in corrosive atmospheres.

At the other end of the range of commercial capacitors the electrolytic type gives the largest capacitance (10,000,000 mmf is common) but with low precision, low stability and the lowest Q. The air capacitor gives us the least capacitance for the given space, but efficiently provides the smallest capacitances with very high precision, high stability and the highest Q.

In general, air capacitors like the familiar type which tunes a home radio follow the construction shown in Fig. 31, varying in size, mounting, mechanical refinements and in the change of capacitance with the angular setting of the shaft. Some types have fixed capacitances.

For operation under high voltage at high frequencies in radio transmitters they are made relatively massive with a large separation between plates to prevent flash-over. This objective is also realized in some commercial types by sealing the unit under vacuum or in an inert gas under high pressure.

Principal Uses of Air Capacitors.

1. Variable tuning.
2. Fixed tuning.

Ceramic Capacitors

The Leyden jar, father of capacitors, with its glass dielectric was a capacitor of the ceramic type. Like most of its descendants today, it had a low capacitance. The present-day ceramic type is used to supply low capacitance values either with electrical characteristics not obtainable with other types or to provide the usual characteristics in a form more economical to manufacture and more convenient to assemble on apparatus panels.

It is commonly made by plating a ceramic tube with metal electrodes, the leads being supplied by wires or terminals soldered to the plating (Fig. 32). The hard, inflexible tube in addition to providing the dielectric also acts as a support

for the electrodes and leads. The tubular form lends itself to efficient space utilization in apparatus assemblies. An incidental advantage of this tubular shape is that it automatically provides separation between leads, a valuable feature in high voltage uses. Because the materials are comparatively nonhygroscopic, a complete coating of varnish is usually a sufficient protection against moisture. For these reasons the ceramic type does not always require the relatively elaborate

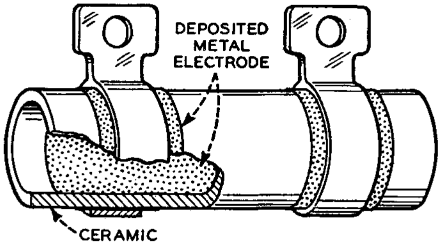


FIG. 32. Ceramic capacitor for higher voltages. Shows use of two capacitance sections in series to reduce corona.

mounting or potting which are so often essential in other types.

Some ceramics rival mica in stability and loss and have the further advantage that they can be molded into a variety of useful shapes. Others can be made to have prescribed capacitance-temperature coefficients. Most ceramics are economically adjustable to close limits of accuracy even when the capacitance is only a few micromicrofarads.

On the debit side many ceramics have considerably lower dielectric strength than most other commercial dielectrics and must therefore be worked at lower electrical stresses.

Glass in the form of Pyrex has had a limited use for low-capacitance, high-precision capacitors in tubular or other forms with plated electrodes and as thin sheets interlocked between metallic foils. In a comparable category is another type consisting of fused-quartz tube with plated electrodes which has been used to supply small, accurate capacitances for tuning high-frequency, high-powered circuits.

A ceramic which is finding increasing use is magnesium orthotitanate which equals mica in low loss, has a higher dielectric constant and may be built for high or low voltage. Barium titanate which has a dielectric constant of 1200 (300 times that of impregnated paper) is used to provide extremely compact capacitors of small capacitance for low-voltage applications.

At the present time, most widely used of all is the Rutile type which can be made to have a specified positive or negative capacitance-temperature coefficient merely by controlling the proportions of titanium dioxide and magnesium orthotitanate in the compound of which the dielectric is made. Rutile capacitors are used to neutralize the effects of positive or negative impedance-temperature changes of coils and networks in circuits which must be held to close adjustment under conditions of swinging temperature.

Principal Uses of Ceramic Capacitors.

1. To compensate for impedance-temperature changes.
2. Fixed tuning at low or high voltage at high frequencies.
3. For circuit-trimming and by-passing purposes particularly where they are more convenient mechanically, smaller or cheaper than alternate types. Variable types in the form of a small tube or disc are available for this use.

CHAPTER 8

Synthetic Dielectrics of the Future

Originally, capacitors of the solid-dielectric type used dielectric materials either immediately employable as found in nature or which can be produced without elaborate chemical transformation; thus mica from muscovite; paper from trees; ceramics from special minerals; oils; and waxes. We have taken these materials as nature made them, merely selecting suitable grades as in the case of mica or eliminating destructive impurities as in the case of paper and oil. However, despite all our efforts—and they are still continuing to make better use of these natural dielectrics—it is likely that we are rapidly approaching the limits of their performance capabilities. In the meantime, the synthetic chemist has been gradually opening up to us a new vista of possibilities by creating dielectrics of radically new composition, through transformation of the basic molecular structure of natural materials.

For example, from trees, flax, cotton and other fibrous plants comes the cellulose fibre of which paper is made. The use of paper in capacitors entails the perpetual problem of eliminating destructive impurities. Now entering the picture is the possibility of using films of synthetic cellulose which are free from the contaminants present in paper; viscose, cellulose esters and cellulose ethers are steps in this direction. In contrast with natural materials, synthetic dielectrics share the great inherent advantage that they can be produced in the first place to a high degree of purity.

The influence of synthetic chemistry has been especially valuable in the field of impregnants for paper capacitors. Here the search for impregnating materials having higher dielectric constants led to a synthetic wax known as chlorinated

naphthalene (Halowax) and a liquid, chlorinated diphenyl (Aroclor or Pyranol). Both are derived from coal-tar products which in turn had their origin in trees and plants which grew and died millions of years ago. Each permits an economy of space not obtainable with the natural waxes and oils which were chiefly used before the development of these synthetics. The use of Halowax notably reduced the size of wax-paper capacitors used in the telephone system; Aroclor has been effectively used to produce low-frequency a-c capacitors which are not only appreciably smaller than their mineral-oil impregnated predecessors but which are also much superior in performance for this particular application.

Indicative of the possibilities of the class of synthetics known as plastics are the unusual characteristics of polystyrene. This flexible material comes in thin sheets which can be wound like paper. Polystyrene capacitors are remarkable for their low a-c loss (that is, high Q) in which respect they equal or excel mica. They are also remarkable for their low dielectric absorption, outstripping even mica in the speed with which they take up and release electric charge; a valuable characteristic in circuits where speedy electrical response is essential.

Usually thought of as being in a class by itself, yet of a purely synthetic type, is the electrolytically-deposited aluminum-oxide dielectric of the electrolytic capacitor. Despite the serious limitations of electrolytic capacitors as they are made today, their performance is nevertheless remarkable when we consider that, in this type, a dielectric film a few millionths of an inch thick can continuously withstand an electrical pressure of 10 million volts per inch. Not only is this film thin enough to give a higher capacitance per volume ratio than any other practical dielectric but it is also tough enough to withstand voltage gradients not attainable in other types of capacitors—two advantages devoutly to be sought in capacitors. Another is the inherent simplicity of the methods whereby the dielectric film may be formed directly on an electrode. Contrast, for example, the relatively elaborate process involved in making the dielectric in impregnated paper

capacitors, nearest rivals to the electrolytics in terms of space economy. First you take a tree and transform it into extra pure, super-thin sheets of paper—a lengthy and detailed process. This paper then has to be cut to size, interleaved with foil electrodes and wound to form the capacitor unit. However, all this is but a prelude to the many hours of drying and vacuum impregnation with a material which was itself the product of processing or manufacture. For the time being, the impregnated paper capacitor which emerges from this more elaborate process can perform services far beyond the capabilities of electrolytics. But, in the long view, it may well turn out that the tenuous, deposited dielectric film in the electrolytic capacitor was the most prophetic as to the future trend.

Synthetic dielectrics constitute a new field on the brink of rapid expansion. Unlike that of the older type capacitors its history is still to be written. At the present time, in selecting a particular type of capacitor because it provides a characteristic which we need, we are often compelled to accept and tolerate other characteristics which are undesirable. As designers and users, we are tempted to dream of a future capacitor which will have the small size of electrolytics, the performance flexibility of paper and the excellent characteristics of mica. Built into its highly-polarizable molecules will be a superlative ruggedness to meet the dual strain of heat and concentrated electric energy. When that prodigy comes into being, can we doubt that it will employ a dielectric created in the laboratory of the synthetic chemist—probably because some enterprising mind was led to ask the right questions about the dielectric properties of the ultimate atom?

CHAPTER 9

Twenty Keys to the Right Capacitor

The capacitor art can probably supply a capacitor satisfactory for your needs. But first you must formulate the requirements. This chapter outlines key questions the answering of which will help you to judge what those requirements should be. The reasons behind these questions are discussed in the foregoing chapters. Naturally some of these questions do not apply to all cases. Accordingly the items are grouped into those which always apply and those which are important only in certain uses. However, as a precaution it is a good idea to consider all of them in every case, setting aside those which obviously do not apply.

Questions Which Apply to All Capacitors.

1. What are the maximum and minimum limits on the capacitance value?

The answer to this foremost question largely determines the type or types of capacitor from which selection must be made and, inferentially, the size and cost. In this matter there are two angles to bear in mind. First, the actual capacitance value of the capacitor when received from the manufacturer differs from the nominal or marked value by a percentage depending on the accuracy to which capacitor was made. Second, when the capacitor is in use in the circuit, the capacitance value will change in unison with changes in frequency and in ambient temperature (Figs. 21, 28 and 29). Added to this is a permanent positive or negative drift in value which occurs as the capacitor "ages" with the lapse of time. The total deviation from the ideal capacitance value is obtained by

adding algebraically the individual positive and negative deviations due to all causes. What are the boundary limits necessary to insure proper performance in our circuit?

Since severe requirements on accuracy may greatly increase the cost of manufacture (and seriously delay production where deliveries are needed within a short period), such requirements should be specified only to the degree that is actually necessary. Another consideration is that where precision characteristics are needed we are usually interested in the precision of the circuit as a whole, that is, in the cumulative deviations of the coils, resistors, transformers and capacitors. Economical design may dictate that it is cheaper to secure the over-all precision required by imposing more severe limits on the other elements of the circuits than on the capacitors. In any event it is always wise to think twice before specifying precision limits.

2. What are the highest and lowest temperatures at which the capacitors will be required to operate?
3. What is the prevailing average temperature of the capacitor?

It can save much trouble if we form the habit of thinking always of the physical and electrical characteristics of a capacitor in terms of temperature since temperature can affect every one of them to an extent important to our use.

4. What will be the prevailing humidity?
5. At what altitude will the capacitor operate with respect to sea level?
6. To what type and severity of mechanical vibration and shock will the capacitor be subjected?
7. Will the capacitor be required to work outdoors or be exposed to corrosive atmospheres such as salt spray?
8. Will the capacitor be used under tropical conditions favorable to the growth of fungus? Also, will fungus on the terminals cause objectionable leakage to ground?

Questions Nos. 2 to 8 (incl.) relate to the physical conditions under which the capacitor is to operate. How we answer them has a vital bearing on the construction of the capacitor and the materials of which it should be made.

Of these physical conditions, none is more important than temperature. Furthermore, the temperature which we must consider is that of the capacitor itself rather than the ambient air temperature. Actual capacitor temperatures depend on a number of factors—thermal conduction from container to apparatus-mounting panel, the proximity of heat-generating apparatus such as tubes and transformers, efficiency of ventilation. Consequently, even in a given apparatus assembly, temperature conditions may differ widely for different capacitors and, just as the use of capacitors suitable only for the more moderate temperatures in the equipment is likely to be hazardous, so the use of capacitors throughout capable of withstanding the highest temperatures may prove unwarrantably costly and space-consuming.

Expansion and contraction incident to temperature change may impair an inadequate seal; sealing materials if unsuitable tend to soften or melt when hot or to harden and crack when cold. Resulting impairment of the seal facilitates the entry of moisture which degrades the dielectric. Is the seal on the capacitor we have in view capable of withstanding the degrees of heat and cold to which it will be exposed?

Humidity, in addition to entering and damaging the dielectric, may condense on inadequate terminal insulation so as to create objectionable current leakage to ground. Poorly protected metal parts corrode in the presence of humidity and this corrosion is especially rapid in the presence of corrosive agents such as salt spray. At high altitudes the lowered air-pressure may reduce the flash-over voltage of terminals to the danger point; in the stratosphere flash-over voltages may be reduced five-fold compared with values for the same terminals at sea level. Vibration or shock tends to break open the container or the seal, move the internal parts so as to impair electrical performance or rip the entire capacitor off the panel.

9. What will be the maximum continuously applied direct voltage?
10. What will be the maximum continuously applied alternating voltage?
11. What will be the frequency of the alternating voltage?
12. Will voltage surges appear across a capacitor and, if so, what will be the peak value?
13. What is the minimum length of operating life required under the operating voltage?

Questions Nos. 9–13 (incl.) are discussed in Chapter 3.

14. Is the frequency of self-resonance important, or the value of the inherent inductance which causes it?

This question arises in high-frequency circuits. Every capacitor resonates with its inherent inductance when the frequency is carried high enough. Below this critical frequency, the reactance is capacitive or negative; above, it is inductive or positive (Fig. 6).

15. What is the maximum tolerable value of direct voltage leakage current between terminals or between terminals and the container?

Under direct voltage a leakage current flows through the dielectric and through stray leakage paths on terminals and other insulation: this current, however small, is never absent. Although usually of no importance from a circuit standpoint, it may become a controlling factor; for example, in grid circuits requiring very low leakage and in circuits required to have precisely-maintained time constants. In applications where the d-c leakage of the capacitor is important, it is well to inquire as to the variation likely to occur in this leakage when the ambient temperature changes and with the capacitor under its operating voltage. This question is perhaps most likely to occur in the use of paper capacitors. In some paper capacitors, the d-c leakage increases ten-fold as the tempera-

ture rises from room temperature to 65° C. Fig. 33 provides a guide as to the variation to be anticipated with paper capacitors using common impregnants. With reference to Fig.

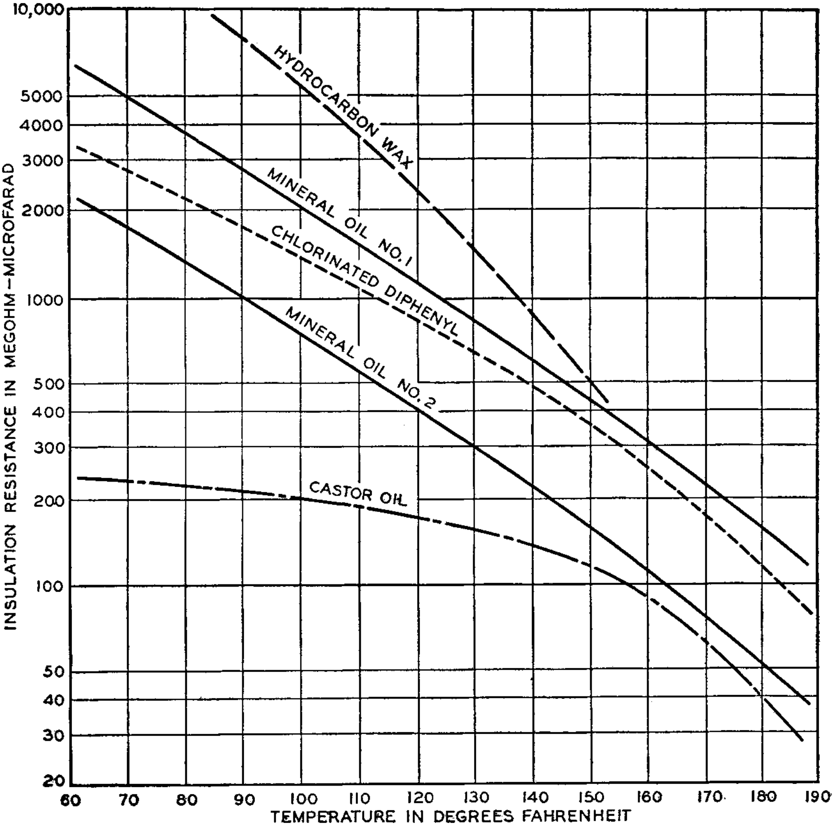


FIG. 33. Insulation versus temperature at 100 volts d-c for paper capacitors using commercial impregnants.

33, because insulation resistance is inversely proportional to the capacitance (except for very small capacitances where the terminal leakage may be controlling), it is commonly expressed in megohm-microfarads. The insulation resistance for a specific capacitance value C is equal to the quantity in megohm-microfarad divided by C, with the answer in megohms.

Precision Capacitors.

1. To what limits of accuracy must the capacitance be adjusted at the factory?
2. At what frequency or frequencies and over what temperature range do these capacitance limits apply? (Figs. 21, 28 and 29.)
3. By what amount is it permissible for the capacitance value to change temporarily when the ambient temperature changes, or permanently as a result of the gradual drift in capacitance value which accompanies "aging"?
4. What is the minimum value of *Q* required?
5. At what frequency or frequencies and over what temperature range does this value of *Q* apply? (Fig. 30.)
6. Is it essential that the capacitor shall meet its capacitance and *Q* requirements over the entire temperature range?

Considerable saving may sometimes be realized by designing to meet precision requirements only over the prevailing temperature range and accepting a somewhat degraded circuit performance at the extreme temperatures.

The *Q*, defined as a ratio of the reactance to the effective series resistance, expresses the fact that the impedance of the capacitor deviates from a pure negative reactance. *Q* varies with frequency and with ambient temperature. Usually the *Q* of a capacitor is so high compared with the *Q* of the circuit as a whole that it may be ignored. It may, however, become critically important in precision circuits; for example, in wave filters required to have low attenuation loss at the transmission-band edges. Is the value of the *Q* of the capacitor important from the standpoint of operation in our circuit? If so, what should be its magnitude and to what extent is it permissible for the *Q* to vary with changing frequency and temperature?

Electrolytic Capacitors.

Will the capacitor remain idle for periods of weeks or months? If so, will it be capable of withstanding the voltage initially applied on resumption of operation?

The latter question is especially important when the capacitor has been stored in a warm place or is hot when the voltage is initially applied.

Ceramic Capacitors.

If the capacitor is to be used to furnish a specific value of capacitance-temperature coefficient, what are the permissible limits of variation in this value?

Air Capacitors.

In what manner should the capacitance value vary with the angle of rotation?

Where the movable plates are to be in frequent motion, will the capacitor, especially the shaft bearings, be able to withstand the motion without serious impairment of accuracy and stability?

When the set will be subject to vibration and the capacitance once adjusted must be held constant, is there sufficient torque resistance in the shaft bearings or dial attachment?

If the capacitor is to operate in a plane, will it be able to withstand the operating voltage without developing corona or flashing over in the rarefied air at high altitudes?

The Final Questions.

Have you *sufficiently* considered to what extent each and all of the foregoing questions may enter into your capacitor problem?

Have you made sure that the manufacturer is fully and accurately informed as to the capabilities the capacitor must have and the conditions under which it is to operate?

EXAMPLES OF TYPICAL CAPACITOR SELECTIONS

The capacitor you need may be evident from a consideration of information provided in commercial catalogs. However, it cannot be too strongly recommended that prospective purchasers of capacitors discuss their problems directly with the manufacturer, particularly where long service and high performance are expected of the equipment.

Some typical examples of how capacitors are selected to meet specific operating conditions, electrical and mechanical, in terms of types now commercially available are shown in Table 2 and discussed below.

Discussion of Capacitor Examples in Table 2.

A. In a power-supply filter in a home radio, a capacitor is required to withstand only a few hundred volts; capacitance limits and Q are unimportant. The paramount need is for a large capacitance of small volume at low cost. The electrolytic type, because of its inherently small size and low cost per microfarad, is usually first choice for this purpose (Chap. 5).

B. In this power-supply filter of a public address system the 600-volt d-c potential is too high for the electrolytic type (Chap. 5). The need for high reliability of performance at low and high temperatures also excludes a wax impregnated paper capacitor and points to a liquid impregnated paper type using castor oil or chlorinated diphenyl with chemical inhibitor (Chap. 6, page 76). Another choice would be mineral oil paper involving, however, some sacrifice in space due to the lower dielectric constant of mineral oil.

Table II

	USE	REQUIREMENTS				TYPE
A	POWER SUPPLY FILTER IN HOME RADIO	16 MF	350 VOLTS DC	40 TO 140 F		ELECTROLYTIC
B	POWER SUPPLY FILTER FOR P. A. SYSTEM	8 MF	600 VOLTS DC	-40 TO 185 F		WITH INHIBITOR PAPER-CHLORINATED DIPHENYL
C	POWER FACTOR CORRECTION	4 MF	300 VOLTS 60 CPS	-40 TO 165 F		PAPER-CHLORINATED DIPHENYL WITH OR WITHOUT INHIBITOR
D	VOLTAGE REGULATED POWER SUPPLY	4 MF	300 VOLTS 60 CPS	0 TO 185 F	CAPACITANCE LIMITS ±10%	PAPER-MINERAL OIL OR TEMPERATURE-STABILIZED CHLORINATED DIPHENYL
E	SUBSCRIBERS TELEPHONE SET	2 MF	50 VOLTS DC	0 TO 120 F		PAPER-HALOWAX
F	HIGH-PRECISION WAVE FILTERS	0.05 MF	50 VOLTS AC	60 TO 100 F	CAPACITANCE LIMITS ±0.3%	SILVERED MICA
G	MODERATE-PRECISION WAVE FILTERS	0.25 MF	50 VOLTS AC	60 TO 100 F	CAPACITANCE LIMITS ±1%	PAPER-HYDROCARBON WAX
H	BYPASS OR AUDIO COUPLING IN HOME RADIO	0.1 MF	LOW DC LEAKAGE	40 TO 140 F	MECHANICAL COMPACTNESS	PAPER-WAX IN TUBULAR CASE
I	ANTENNA COUPLING NETWORK FOR GROUND RADIO	50 MMF	4 AMP. AT 4 TO 10 MC	40 TO 165 F	CAPACITANCE LIMITS ±10%	IMPREGNATED MICA
J	SAME AS I, FOR AIRPLANE RADIO	50 MMF	4 AMP. AT 4 TO 10 MC	-40 TO 185 F	CAPACITANCE LIMITS ±10% SMALL SIZE AND WEIGHT PARAMOUNT	CERAMIC OR VACUUM TYPE
K	SUPPRESS RADIO INTERFERENCE ON SMALL MOTOR	0.001 MF	200 VOLTS PEAK DC	40 TO 220 F	PHYSICAL COMPACTNESS PARAMOUNT	MICA OR CERAMIC
L	TEMPERATURE COMPENSATION IN VACUUM TUBE OSCILLATOR	250 MMF	100 VOLTS PEAK DC	40 TO 150 F	NEGATIVE TEMP. COEFF. 100 PARTS PER MILLION PER DEGREE F	CERAMIC
M	VARIABLE TUNING	10 TO 400 MMF	GOOD ELEC. CONTACT	STABLE UNDER VIBRATION, HEAT AND HUMIDITY		AIR

C. For power factor correction over a wide operating temperature range, the paper chlorinated diphenyl type, preferably of the type having capacitance-temperature stabilization (Fig. 25), is easily the first choice, both as to size and endurance under 60-cycle voltage. Here again next best choice would be a mineral-oil unit of larger size.

D. In this voltage-regulated power supply the capacitance value must not deviate by more than ± 10 per cent due to all causes. In judging whether a capacitor will meet these deviation limits we must take into account not only the initial capacitance tolerance at the time of manufacture but also the probable changes in service due to temperature and aging. For example, if our selection is to be a mineral-oil paper capacitor, then we can expect a variation of the order of ± 1 per cent relative to 70° F (Fig. 25). Aging may be expected to contribute ± 1 per cent. So temperature and aging changes may total ± 2 per cent. The difference between ± 10 per cent and ± 2 per cent, namely ± 8 per cent, represents the limits to which the capacitance must be adjusted in the factory. Information on the capacitance stability of specific types is usually obtainable from the manufacturer.

E. In a telephone subscriber's set, the capacitor usually works under lenient conditions of temperature and humidity and the voltage is low. Long service life and reliability are prime requirements while capacitance limits and Q are of secondary importance. Here the Halowax-paper capacitor with inexpensive asphalt or wax sealing, offers a compact and economical solution. However, in the tropics or the arctic, similar telephone equipment might call for more expensive and larger capacitors made with different impregnants and hermetic seals suitable for extreme heat, cold or humidity.

F. In electric wave filters, precise location of the pass-frequency band imposes narrow capacitance limits. Also the Q must be high to insure satisfactory discrimination against unwanted frequencies at the cut-off points of the pass-band. In cases where the highest precision and stability are required, mica capacitors, preferably of silvered mica construction (Figs. 28, 29 and 30), are indicated.

G. For the wave filters where requirements for precision and stability are much less exacting than in Example *F* and where higher capacitances are involved as, for example, in audio-frequency filters, the hydrocarbon wax impregnated paper capacitor offer the economical solution. The smaller Halowax-type capacitor could afford neither the capacitance stability nor the Q of the hydrocarbon type. Working at room temperatures under normal conditions of humidity, the capacitor may be adequately sealed with asphalt or wax. Wider temperature ranges or severe conditions of humidity would call for more expensive and larger mineral-oil impregnated capacitors with hermetic seals.

H. For by-pass and audio-frequency coupling in a home radio, paper capacitors in tubular casings mounted by their wire leads supply the needed mechanical compactness. Under temperate indoor conditions, a tubular casing of waxed cardboard may be sufficient protection, but at higher humidities, for example, along sea coast locations and in tropical climates, the cardboard might take in sufficient water to cause dielectric failure especially if the capacitor is worked close to its voltage rating. In addition, if the capacitor is for grid-plate coupling, the absorbed water might seriously impair the needed low, direct-current leakage. In such cases a metal-encased, hermetically-sealed, tubular type is indicated. For cathode resistor by-pass purposes where the voltage is low and the leakage unimportant,

the cardboard tube casing proves generally satisfactory.

I. A capacitor working in the coupling network of a radio transmitting antenna is required to handle considerable current at high frequencies. This calls for low-loss dielectrics among which are air, mica, certain ceramics and synthetics. A paper capacitor with its relatively high loss at high frequencies would be out of the question. Mica capacitors available for this purpose provide a satisfactory solution.

J. As in example *I,* this capacitor also works with a radio transmitting antenna but the antenna is on a plane and there are severe limitations on both space and weight. For the example cited, a ceramic- or a vacuum-type capacitor can provide a smaller and lighter unit than the mica type with equal electrical performance.

K. This capacitor for the suppression of radio interference must be of suitable size and shape for mounting on a small commutator-type motor. It must withstand the maximum voltage at the high temperature engendered by the heat from the motor. Because of the small capacitance the usual choice would be a small molded mica or a ceramic type, depending on space and mounting conditions.

L. In this example of a fixed-frequency, vacuum-tube oscillator, tuned by an air capacitor set at 250 mmf, the frequency drifts objectionably with changing temperature at a rate of minus 50 parts per million per °F. Usually, as a first approximation, it may be assumed that such a drift is due to cumulative changes in parts of the circuit other than the air capacitor. In this case this residual capacitance in the circuit increases as the temperature rises. So this oscillator may be stabilized with respect to changing temperature by endowing the tuning capacitance with a negative coefficient. Also the magnitude should be 100 parts per million (capacitance is inversely proportional to the

square of the frequency but where the changes are small the capacitance change is equal to approximately twice the frequency change). To perform this compensating function, temperature-compensating ceramic capacitors are available.

The other course is to replace only part of the 250 mmf by a ceramic. In that case, however, the ceramic being of smaller capacitance must be given a larger coefficient to provide the full compensation needed.

M. This air capacitor is required to provide variable tuning through push-buttons for an automobile radio broadcast receiver. The capacitor must have sufficient mechanical and electrical stability to insure that the capacitance value for each predetermined setting is exactly maintained under vibration, heat and humidity. This can be secured by using ceramic insulation and by soldering the individual plates to their supports. Contacts should be corrosion-resistant to insure the good electrical contact essential to noise-free operation. Non-ferrous plates and contacts are preferred.

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